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Toward a Taylor rule for fiscal policy

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Abstract

This paper presents a procedure to determine policy feedback rules in dynamic stochastic general equilibrium (DSGE) models. We illustrate our approach with fiscal feedback rules for tax instruments in a standard medium-scale DSGE model. First, we approximate the optimal dynamic behavior of the economy using simple linear feedback rules. Then we calculate the elasticities of the model variables' moments with respect to the feedback coefficients. The feedback coefficients associated with the highest elasticities form the policy feedback rules to be estimated. Our results stress the importance of carefully modeled fiscal tax policy in two dimensions: (i) with respect to the dynamic responses of fiscal policy to exogenous shocks and (ii) with respect to the historical shock decomposition of fiscal policy.

JEL classification: E62, H30, C51.

Keywords: Fiscal policy, Bayesian model estimation, Identification

Non-technical Summary

In a dynamic stochastic general equilibrium (DSGE) model, fiscal policy instruments have thus far been commonly characterized by feedback rules. The specification of these rules is not an innocuous choice. Still, the rules are either modeled as simple ad-hoc processes or based on the assumption of a welfare-optimizing policymaker. However, the former probably assumes too little purposeful action by the policymaker, while the latter implies an omnipotent and omniscient decision-maker. Both ways thus constitute extreme and in this respect unsatisfying approaches to explain and to understand past and current fiscal policy. By contrast, we propose an intermediate and thus more realistic approach which we illustrate with an application for tax policy. In our setup, the policymaker faces a set of variables of interest she wants to influence with tax instruments. We compute the elasticities of these variables' moments with respect to a wide range of policy feedback coefficients. The feedback coefficients associated with the strongest impact on variables' moments constitute the simple and linear feedback rules, which are then estimated. In a nutshell, the contribution of this paper is how to efficiently choose the variables in policy feedback rules. This represents a further step toward empirically and theoretically founded fiscal feedback rules - similar to the standard Taylor rule in monetary economics.

The approach in the present paper is, however, applicable for various policy feedback rules. In our application, we determine the feedback rules for taxes on capital income and labor income. In particular, for both tax rates we identify feedback coefficients on investment and on lagged tax rates as important for variables' moments. For the same reason, the labor income tax rule further includes a feedback coefficient on hours worked. When estimating the model closed by these policy feedback rules, we identify and estimate all coefficients except for the labor income tax rate's coefficient on private investment as different from zero. While both estimated feedback rules contain pro-cyclical as well as counter-cyclical elements, the estimated impulse response functions are counter-cyclical. Both tax rates rise during a boom. These implications for tax policy are different from the estimated tax policy for the model closed with ad-hoc rules, where fiscal policy is set pro-cyclical. This finding emphasizes the importance of carefully modeled fiscal feedback rules. In addition, the importance of carefully modeled fiscal policy is further stressed by the historical shock decomposition of the average tax rates. Importantly, the more elaborate tax rules capture endogenous systematic adjustments better and can more clearly distinguish between automatic stabilizing policy and exogenous tax shocks.

Nicht-technische Zusammenfassung

Gegenwärtig wird in dynamisch-stochastischen Gleichgewichtsmodellen (DSGE) die Fiskalpolitik durch Feedbackregeln beschrieben. Diese Regeln basieren entweder auf sehr einfachen ad-hoc Überlegungen oder unterstellen Politiker, die die Wohlfahrt maximieren. Während die erste Annahme eine wenig zielorientierte Politik unterstellt, geht die zweite Annahme von einem allwissenden und allmächtigen Politkentscheider aus. Insofern sind diese Vorgehensweisen nicht nur methodisch unbefriedigend, sondern sie basieren auch auf extremen Annahmen, die ungeeignet erscheinen, um gegenwärtige und vergangene Fiskalpolitik zu beschreiben. Im Gegensatz dazu unterstellen wir einen zwischen diesen Extremen liegenden und damit realistischeren Ansatz, welchen wir anhand von Steuerpolitik illustrieren. In dem von uns gewählten Ansatz hat der Politikentscheider ein Bündel von Variablen, die er mit Steuerpolitikinstrumenten beeinflussen will. Wir berechnen die Elastizitäten dieser Variablen im Hinblick auf eine Vielzahl möglicher Feedbackkoeffizienten. Die Feedbackkoeffizienten mit dem stärksten Einfluss auf die Variablen bilden die Basis für unsere relativ einfachen und linearen Feedbackregeln, die wir anschließend schätzen. Aus methodischer Sicht liegt der Beitrag dieses Papiers darin, aufzuzeigen, wie man Variablen innerhalb von Feedbackregeln allgemein bestimmen kann. Dieser Beitrag repräsentiert damit einen weiteren Schritt hin zu empirisch wie auch theoretisch fundierten fiskalpolitischen Regeln - vergleichbar mit der Taylor-Regel für die Geldpolitik.

In der von uns gewählten Anwendung identifizieren wir die Feedbackvariablen für Steuersätze auf Kapitaleinkommen sowie auf Einkommen aus Arbeit. Es zeigt sich, dass für beide Steuersätze sowohl die Koeffizienten der Investitionen als auch die Koeffizienten der jeweils vorangegangenen Steuersätze die Elaszitäten der Variablen stark beeinflussen. Darüber hinaus sind die geleisteten Arbeitsstunden eine wichtige Feedbackvariable für die Steuer auf Einkommen aus Arbeit. Die anschließende Schätzung des Modells inklusive der neu bestimmten Feedbackregeln identifiziert alle Parameter ungleich null, mit Ausnahme des Feedbackkoeffizienten auf Investitionen innerhalb der Steuerregel des Arbeitseinkommens. Beide Steuerregeln beinhalten sowohl prozyklische als auch antizyklische Elemente, aber letztendlich ist die geschätzte Impulsantwortfunktion antizyklisch. Dementsprechend steigen die Steuersätze während eines Aufschwungs und wirken somit konjunkturdämpfend im Gegensatz zu einer geschätzten Steuerpolitik bei der einfache ad-hoc Steuerfunktionen unterstellt werden. Dort wirkt die Steuerpolitik prozyklisch. Der Vorteil unserer Vorgehensweise wird auch dann deutlich, wenn man die historische Zerlegung der Steuersätze untersucht. Unsere ermittelten Steuerregeln sind im Vergleich zu den ad-hoc Regeln besser in der Lage, systematische, endogene Änderungen der Steuersätze zu beschreiben. Dadurch ist letztendlich eine bessere Unterscheidung zwischen endogenen und exogenen Steueränderungen möglich.

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TOWARD A TAYLOR RULE FOR FISCAL POLICY[*]

1 Introduction

In a dynamic stochastic general equilibrium (DSGE) model, fiscal policy instruments have thus far been commonly characterized by feedback rules. The specification of these rules is not an innocuous choice (Cúrdia and Reis, 2010). Still, the rules are either modeled as simple ad-hoc processes or based on the assumption of a welfare-optimizing policymaker. However, the former probably assumes too little purposeful action by the policymaker, while the latter implies an omnipotent and omniscient decision-maker. Both ways thus constitute extreme and in this respect unsatisfying approaches to explain and to understand past and current fiscal policy. By contrast, we propose an intermediate and thus more realistic approach which we illustrate with an application for tax policy. In our setup, the policymaker faces a set of variables of interest she wants to influence with tax instruments. We compute the elasticities of these variables' moments with respect to a wide range of policy feedback coefficients. The feedback coefficients associated with the strongest impact on variables' moments constitute the simple and linear feedback rules, which are then estimated. In a nutshell, the contribution of this paper is how to choose

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the variables in policy feedback rules. This represents a further step toward empirically and theoretically founded fiscal feedback rules - similar to the standard Taylor rule in monetary economics.

The approach in the present paper is applicable to various policy feedback rules. In our application, we determine the feedback rules for taxes on capital income and labor income within a standard medium-scale DSGE model such as proposed by Schmitt-Grohé and Uribe (2006, 2007). In particular, for both tax rates we identify feedback coefficients on investment and on lagged tax rates as important for variables' moments. For the same reason, the labor income tax rule further includes a feedback coefficient on hours worked. When estimating the model closed by these policy feedback rules, we identify and estimate all coefficients except for the labor income tax rate's coefficient on private investment as different from zero. While both estimated feedback rules contain pro-cyclical as well as counter-cyclical elements, the estimated impulse response functions are counter-cyclical. Both tax rates rise during a boom. These implications for tax policy are different from the estimated tax policy for the model closed with ad-hoc rules, where fiscal policy is set pro-cyclical. This finding emphasizes the importance of carefully modeled fiscal feedback rules. In addition, the importance of carefully modeled fiscal policy is further stressed by the historical shock decomposition of the average tax rates. Importantly, the more elaborate tax rules capture endogenous systematic adjustments better and can more clearly distinguish between automatic stabilizing policy and exogenous tax shocks.

We think of the DSGE model as containing two sets of behavioral equations: one describing the private sector and one describing the fiscal policy sector. The private sector is solely characterized by the solution to the households' and firms' problems and the corresponding structural model parameters. To capture and describe the model's private sector, we estimate the model using Bayesian model estimation techniques. Given the estimates of the structural parameters, we compute the optimal taxation policy. Since the optimal policy rules are highly non-linear and complex, we aim at approximating them by simple, linear feedback rules. To do so, we first choose a set of variables which describe the optimal dynamic behavior of the economy well, e.g. output, private investment, nominal interest rate, hours worked, and private consumption. Given a sequence of exogenous shocks, we simulate the time series of these variables. In order to be agnostic about the correct feedback variables in the policy rule, we start by estimating general policy rules. The estimated policy rules are employed to compute the elasticities of the model variables' moments with respect to the feedback coefficients in the policy rule. The elasticities are calculated based on the approach proposed by Iskrev (2010). This allows us to identify the variables fiscal policy can affect and to rank the feedback variables according to their importance for the optimal dynamic behavior of the policymakers' chosen variables of interest. The policy feedback rules for the DSGE model are then determined by picking the most important feedback variables for each policy instrument with respect to variables of interest. Then, we re-estimate the DSGE model including the previously derived policy rules. This is necessary to check the policy invariance of the private sector estimates and to verify the empirical relevance of the feedback variables.

The present paper extends the recent literature in various ways. Building on the work of Baxter and King (1993), Galí, López-Salido, and Vallés (2007), and Leeper and Yang (2008), recent studies have sought to empirically characterize the behavior of the fiscal policy sector. Forni, Monteforte, and Sessa (2009) characterize fiscal policy in a simple way by estimating feedback rules on debt. The authors argue for the importance of automatic stabilizers and their inclusion in the feedback rules, but, because of no empirical evidence, they neglect such additional feedback variables and just focus on government debt. Jones (2002) assumes that fiscal policy responds to current and lagged output as well as hours worked. Leeper, Plante, and Traum (2009) include output as an additional variable in the policy rules and consider potential correlations of the tax rates. The former class of models has in common that the choice of fiscal policy coefficients appears to motivated by several considerations, yet lacks a model-consistent or theoretical foundation. Since there is no role for government debt in common DSGE models, there is no reason for the policymaker to respond to changes in government debt. However, there are good reasons to include debt in the feedback rules: from an empirical point of view (Bohn, 1998) and to ensure the stability of the model. In addition, we show that the choice of output, to capture the behavior of automatic stabilizers with respect to the business cycle, is not efficient from the perspective of a policymaker who knows the most important feedback variables.

Another strand of the literature investigates fiscal policy from a welfare-maximizing perspective. Benigno and Woodford (2006b) evaluate optimal fiscal rules by deriving the correct feedback variables as well as corresponding parameter loadings by using their linear quadratic approach (Benigno and Woodford, 2006a). However, this approach is not implementable for the class of larger models. It is worth mentioning that the approach in the present paper is more flexible with respect to the underlying target of the policymaker.

Schmitt-Grohé and Uribe (2004, 2006) estimate feedback parameters of simple monetary and fiscal policy rules to mimic the dynamic behavior of the welfare-optimizing Ramsey planner. Moreover, Schmitt-Grohé and Uribe (2007) determine optimal and simple feedback rules by maximizing a second-order welfare approximation of the model. The setup of our work is closely related to these papers, but ours differ in two important aspects. First, and most important, the motivation of our approach is to determine the important feedback variables to mimic the optimal dynamic behavior of the welfare-optimizing policymaker. The final optimized simple linear rules are optimized with respect to their feedback variables rather than to their parameter loadings. Second, we use a full-fledged maximum likelihood estimation approach instead of the method of moments estimation or second-order welfare maximization when approximating the optimal policy rules with linear feedback rules. The additional information contained in the maximum likelihood approach makes it more efficient in terms of optimization and enables us into the position to start with a much larger and more agnostic policy rule.

The remainder of the paper is organized as follows. Section 2 describes the benchmark model and its estimation. In section 3 we present the methodology to determine the policy rules. In section 4 we present the estimated extended policy rules and discuss the consequences. Section 5 concludes.

2 Benchmark Economy

In this section, we initially set up the benchmark economy, for which we derive the fiscal policy rules. To describe the private sector behavior, we estimate this model using Bayesian estimation methods. Moreover, we provide information about the data set, discuss the choice of the prior distribution, and present the estimation results.

2.1 Choice of the Benchmark Model

We assume that the the benchmark economy can be described by a conventional New Keynesian DSGE model. The model includes several real frictions: internal habit formation, capital utilization, and investment adjustment costs. It also comprises two nominal rigidities for wages and prices, both following the adjustment process postulated by Calvo (1983). The fiscal policy sector is modeled following Benigno and Woodford (2006b) with wasteful government spending and distortionary taxes on capital and wages but also lump-sum taxation.

When choosing the benchmark model for the illustration of our approach to determine policy feedback rules for tax instruments, we are faced with the trade-off that the model should not be too simple in order to approximate the private sector, but it should be also widely known and accepted as a standard and state-of-the-art model. The benchmark model presented here, as in the succession of Christiano, Eichenbaum, and Evans (2005), and Smets and Wouters (2007), meets both requirements. It is designed to capture the behavior of the private sector well and is widely acknowledged as one of the workhorses in dynamic macroeconomics. However, using that standard model comes at some cost. It contains a government sector, including feedback rules for distortionary tax rates. But, its fiscal policy is still modeled as an artifact, i.e. it has no actual role. We stick with the model since, firstly, it is close to the related literature and our results are thus more comparable and, secondly, it is a model with which researchers have recently been aiming to replicate a fiscal policy sector.

In order to obtain estimates for the private sector on the basis of which we will then derive the fiscal policy rules, we first estimate the model with simple fiscal feedback rules.

2.2 Model Description

Throughout the model description, capital letters denote nominal variables and lower-case letters real variables. An exception is investment, which is always expressed in real terms as I.

Households

In the economy there exists a continuum of households indexed by $i \in [0,1]$. Each household i consumes $c\left(i\right)$ and provides labor services $l\left(i\right)$. Consumers' preferences are characterized by the discount factor β, the inverse of the intertemporal substitution elasticity σ_c, the inverse of the labor supply elasticity with respect to wages σ_l, and one parameter scaling the disutility of labor ψ_l. The parameter h measures the internal habit persistence regarding consumption. Utility takes the following functional form:

$$E_t \sum_{t=1}^{\infty} \beta^t \left[\frac{\left(c_t\left(i\right) - hc_{t-1}\left(i\right)\right)^{1-\sigma_c}}{1-\sigma_c} - \psi_l \frac{l_t\left(i\right)^{1+\sigma_l}}{1+\sigma_l} \right] \tag{1}$$

Household i holds government bonds B yielding return R. Government bonds are subject to a shock ε_q that introduces a wedge between the interest rate controlled by the monetary authority and the government bonds. This risk premium shock follows the autoregressive process

$$\log \varepsilon_{q,t} = \rho_q \log \varepsilon_{q,t-1} + \epsilon_t^q, \tag{2}$$

with ϵ^q *i.i.d.* distributed. The household further invests $I\left(i\right)$ into capital k. The rental rate on capital is denoted by r^k and firms' dividends by d. Wages W are set according to a Calvo wage-setting scheme. The household pays lump-sum taxes (or receives transfers) τ^L as well as distortionary taxes τ^w and τ^k on labor income and capital income, respectively.

The utilization rate of capital can be varied equivalently to the assumption made by Smets and Wouters (2007). The cost of capacity utilization is given by $\phi(\cdot)$. We assume the functional form:

$$\phi_t\left(u\right) = \frac{(1-\bar{\tau}_k)\bar{r}^k}{\sigma_u}\left(\exp\left(\sigma_u\left(u_t-1\right)\right)-1\right) \tag{3}$$

Capital depreciates at a constant rate δ. Investments are subject to a convex investment adjustment cost $s\left(\cdot\right)$

$$s_t\left(\frac{\varepsilon_{i,t}I_t}{I_{t-1}}\right) = \frac{\nu}{2}\left(\frac{\varepsilon_{i,t}I_t}{I_{t-1}}-1\right)^2, \tag{4}$$

where ε_i denotes an investment-specific efficiency shock to the adjustment costs and is supposed to follow an autoregressive process

$$\log\varepsilon_{i,t} = \rho_i\log\varepsilon_{i,t-1}+\epsilon_t^i, \tag{5}$$

with ϵ^i assumed to be *i.i.d.* distributed. Capital accumulation is described by

$$k_t\left(i\right) = \left(1-\delta\right)k_{t-1}\left(i\right)+\left[1-s_t\left(\frac{\varepsilon_{i,t}I_t}{I_{t-1}}\right)\right]I_t\left(i\right). \tag{6}$$

To ensure homogeneity of the households with respect to consumption and asset holdings, but heterogeneity with respect to wages and hours worked in equilibrium, households receive the net cash flow from state-contingent securities ι (see e.g. Christiano et al., 2005).

Summarizing the previous paragraphs, the household's per-period budget constraint is given by

$$\begin{aligned} c_t\left(i\right)+I_t\left(i\right)+b_t\left(i\right) = & \left(1-\tau_t^w\right)\frac{W_t\left(i\right)}{P_t}l_t\left(i\right)+\left(\left(1-\tau_t^k\right)r_t^k u_t\left(i\right)-\phi_t\left(u\left(i\right)\right)\right)k_{t-1}\left(i\right) \\ & +\frac{\varepsilon_{q,t-1}R_{t-1}b_{t-1}\left(i\right)}{\pi_t}+(1-\tau_t^k)d_t\left(i\right)+\iota_t\left(i\right)+\tau_t^L. \end{aligned} \tag{7}$$

Maximizing utility (1) subject to the budget constraint (7) and the capital accumulation equation (6) with respect to c, k, u, b and I yields the following first-order conditions:[1]

$$\chi_t = (c_t - hc_{t-1})^{-\sigma_c} - \beta h(c_{t+1} - hc_t)^{-\sigma_c} \tag{8}$$

$$\frac{1}{R_t^b} = \beta \frac{\chi_{t+1}\varepsilon_{q,t}}{\chi_t \pi_{t+1}^p} \tag{9}$$

$$q_t = \beta E_t \left[\frac{\chi_{t+1}}{\chi_t} \left(\psi'\left(u_{t+1}\right) u_{t+1} - \psi\left(u_{t+1}\right) + q_{t+1}\left(1-\delta\right) \right) \right] \tag{10}$$

$$\phi_t' = r_t^k \left(1 - \tau_t^k\right) \tag{11}$$

$$q_t = \frac{1 - \beta E_t \left[\frac{\chi_{t+1}}{\chi_t} q_{t+1} s_{t+1}' \varepsilon_{i,t+1} \left(\frac{I_{t+1}}{I_t} \right)^2 \right]}{1 - s_t - s_t' \frac{\varepsilon_{i,t} I_t}{I_{t-1}}} \tag{12}$$

In the foregoing equations, χ_t denotes the marginal utility of consumption and q_t the marginal utility of capital relative to the marginal utility of consumption.

LABOR MARKET

Wage setting is modeled following Erceg, Henderson, and Levin (2000), i.e. analogously to staggered price setting. Each household supplies a differentiated type of labor service, $l(i)$, which is aggregated into a homogenous labor good by a representative competitive firm (labor packer) according to a Dixit-Stiglitz aggregator with $\theta_w > 1$ denoting the elasticity of substitution

$$l_t^d = \left[\int_0^1 l_t\left(i\right)^{\frac{\theta_w - 1}{\theta_w}} \right]^{\frac{\theta_w}{\theta_w - 1}}. \tag{13}$$

Minimizing costs $W_t l_t^d$ and taking the individual wage costs of household i, $W_t(i)$, as given yields the demand for labor of type i as

$$l_t(i) = \left[\frac{W_t\left(i\right)}{W_t} \right]^{-\theta_w} l_t^d, \tag{14}$$

and the definition of the wage index W_t as

$$W_t = \left[\int_0^1 W_t\left(i\right)^{\theta_w - 1} \right]^{\frac{1}{\theta_w - 1}}.$$

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[1] Since the first-order conditions for household i are identical to the first-order conditions after aggregation, we report the aggregated first-order conditions for the sake of space.

For any wage rate, each household supplies as many labor services as demanded.

In each period, household i is allowed to set its wage with probability $1-\gamma_w$. Household i chooses its optimal wage $W_t^\star = W_t(i)$ by maximizing the objective function

$$\max_{W_t(i)} \quad E_t\left[\sum_{k=0}^{\infty}(\gamma_w\beta)^k\left[\chi_{t+k}W_t\left(i\right)l_{t+k}\left(i\right)-U\left(l_{t+k}\left(i\right),c_{t+k}\left(i\right)\right)\right]\right]. \tag{15}$$

The corresponding first-order condition is given by

$$E_t\left[\sum_{k=0}^{\infty}(\gamma_w\beta)^k\left[\frac{W_t\left(i\right)}{P_{t+k}}l_{t+k}\left(i\right)-\frac{\theta_w-1}{\theta_w}MRS_{t+k}\left(l_{t+k}\left(i\right),c_{t+k}\left(i\right)\right)\right]\right]=0, \tag{16}$$

where $MRS = -\frac{U_l}{U_c}$ is defined as the marginal rate of intratemporal substitution between consumption and labor. If the household is not allowed to set its wage, wages are adjusted by the steady-state inflation rate of the economy $\bar{\pi}$:

$$W_t(i) = \bar{\pi}W_{t-1}(i). \tag{17}$$

The nominal aggregate wage thus evolves according to the following process:

$$W_t = \left[\gamma_w\left(\bar{\pi}W_{t-1}\right)^{1-\theta_w} + \left(1-\gamma_w\right)\left(W_t^\star\right)^{1-\theta_w}\right]^{\frac{1}{1-\theta_w}} \tag{18}$$

By defining the real wage inflation π^w as

$$\pi_t^w = \frac{w_t}{w_{t-1}}\pi_t \tag{19}$$

and using our definition of the labor demand eq. (14), we re-write equation (16) in recursive form as:

$$K_t^w = \left(l_t^d\right)^{1+\sigma_l} + \beta\gamma_w\left(\frac{\bar{\pi}}{\pi_{t+1}^w}\right)^{-\theta_w(1+\sigma_l)}K_{t+1}^w \tag{20}$$

$$F_t^w = \frac{(\theta_w-1)}{\theta_w}\left(1-\tau_t^w\right)l_t^d\chi_t + \beta\gamma_w\left(\frac{\pi_{t+1}}{\pi_{t+1}^w}\right)^{-\theta_w}\left(\frac{\bar{\pi}}{\pi_{t+1}}\right)^{1-\theta_w}F_{t+1}^w \tag{21}$$

$$\frac{K_t^w}{F_t^w} = \frac{1}{\psi_l}\left(w_t^*\right)^{1+\theta_w\sigma_l}w_t \tag{22}$$

Equation (18) is employed to determine the law of motion for $w_t^* = \frac{W_t^\star}{W_t}$:

$$1 = \gamma_w \left(\frac{\bar{\pi}}{\pi_t^w} \right)^{1-\theta_w} + (1 - \gamma_w) \left(w_t^* \right)^{1-\theta_w} \tag{23}$$

Firms

The economy consists of two sectors. In one sector, perfectly competitive firms produce the final good y using as inputs intermediate goods $y(j)$ produced by monopolistically competitive firms indexed by j.

Final-goods firms have access to the constant-returns-to-scale production function with elasticity of substitution θ_p

$$y_t = \left[\int_0^1 y_t\left(j\right)^{\frac{\theta_p - 1}{\theta_p}} \right]^{\frac{\theta_p}{\theta_p - 1}}, \tag{24}$$

Cost minimization yields the demand for each intermediate good

$$y_t\left(j\right) = \left[\frac{P_t}{P_t\left(j\right)} \right]^{\theta_p} y_t, \tag{25}$$

with the corresponding price index

$$P_t = \left[\int_0^1 P_t\left(j\right)^{1-\theta_p} \right]^{\frac{1}{1-\theta_p}}. \tag{26}$$

The intermediate goods are produced by an existing continuum of monopolistically competitive firms $j \in [0, 1]$ using the production function

$$y_t\left(j\right) = \left(u_t k_{t-1}\left(j\right)\right)^{\alpha} \left(l_t^d\left(j\right) \varepsilon_{z,t}\right)^{1-\alpha} - \Omega, \tag{27}$$

where α denotes the output elasticity with respect to capital and Ω fixed costs of production. The assumption of fixed costs is made to ensure that the production function exhibits increasing returns to scale. The variable ε_z represents a labor-augmenting productivity shock assumed to follow the process

$$\log \varepsilon_{z,t} = \rho_z \log \varepsilon_{z,t-1}. + \epsilon_t^z \tag{28}$$

Firms maximize profits:

$$\max_{u_t \cdot k_{t-1}, l_t} \left[\left[\frac{P_t\left(i\right)}{P_t} \right]^{-\theta_p} \left(y_t\left(j\right) - w_t l_t\left(j\right) - r_t^k u_t k_{t-1}\left(j\right) \right) \right] \tag{29}$$

Denote marginal costs by z. The first-order conditions of (29) are given by:

$$z_t\left(1-\alpha\right)\left(u_t k_{t-1}\right)^{\alpha}\left(l_t^d \varepsilon_{z,t}\right)^{-\alpha} = w_t \tag{30}$$

$$z_t \alpha \left(u_t k_{t-1}\right)^{\alpha-1}\left(l_t^d \varepsilon_{z,t}\right)^{1-\alpha} = r_t^k \tag{31}$$

The profits of the intermediate firm are then defined as

$$d_t = y_t - r_t^k u_t k_{t-1} - w_t l_t^d. \tag{32}$$

Intermediate-good firms are subject to staggered price setting, i.e. they are allowed to adjust their prices with probability $(1-\gamma_p)$. Price-resetting firms choose $P_t^{\star} = P_t\left(j\right)$ to maximize the expected sum of discounted future profits:

$$\max_{P_t(j)} \quad E_t \sum_{k=0}^{\infty} \gamma_p^k m_{t+k} \left[P_t\left(j\right) y_{t+k}\left(j\right) - Z_{t+k} y_{t+k}\left(j\right) \right] \tag{33}$$

Future profits are discounted by a stochastic discount $m_{t+j} = \beta^j \frac{\chi_{t+j} P_t}{\chi_t P_{t+j}}$. The first-order condition of this maximization problem implies that prices in period t are set according to

$$P_t^{\star} = \frac{\theta_p}{\theta_p - 1} \frac{E_t \left[\sum_{k=0}^{\infty} \gamma_p^k m_{t+k} z_{t+k} y_{t+k}\left(j\right) P_{t+k} \right]}{E_t \left[\sum_{k=0}^{\infty} \gamma_p^k m_{t+k} \bar{\pi}^k y_{t+k}\left(j\right) \right]}. \tag{34}$$

Prices of firms which cannot re-optimize evolve according to $P_t\left(i\right) = \bar{\pi} P_{t-1}$. The overall price level is therefore given by:

$$P_t = \left[\gamma_p \left(\bar{\pi} P_{t-1} \right)^{1-\theta_p} + \left(1-\gamma_p\right) \left(P_t^{\star} \right)^{1-\theta_p} \right]^{\frac{1}{1-\theta_p}} \tag{35}$$

Defining $p_t^* = \frac{P_t^*}{P_t}$, and making use of equations (25) and (35), the first-order condition (34) and the law of motion for p_t^* are recursively written as:

$$F_t^p = y_t^d \chi_t + \gamma_p \beta \left(\frac{\bar{\pi}}{\pi_{t+1}} \right)^{1-\theta_p} F_{t+1}^p \tag{36}$$

$$K_t^p = \frac{\theta_p}{\theta_p - 1} y_t^d \chi_t z_t + \gamma_p \beta \left(\frac{\bar{\pi}}{\pi_{t+1}} \right)^{-\theta_p} K_{t+1}^p \tag{37}$$

$$\frac{K_t^p}{F_t^p} = p_t^* \tag{38}$$

$$1 = \gamma_p \left(\frac{\bar{\pi}}{\pi_t} \right)^{1-\theta_p} + (1 - \gamma_p) \left(p_t^* \right)^{1-\theta_p} \tag{39}$$

POLICY SECTOR

The monetary authority sets nominal interest rates according to a Taylor rule that includes lagged nominal interest rates, lagged output, current inflation, and an *i.i.d.* monetary policy shock ϵ^m:

$$\log R_t = \rho_R \log R_{t-1} + (1 - \rho_R) \left(\bar{R} + \rho_\pi \left(\log \pi_t - \log \bar{\pi} \right) + \rho_y \left(\log y_{t-1} - \log \bar{y} \right) \right) + \epsilon_t^m \tag{40}$$

The fiscal authority receives tax revenues x and issues bonds b to finance government consumption expenditure c^g. The government budget constraint therefore reads as:

$$\left[\frac{b_t \pi_{t+1}}{\varepsilon_{q,t} R_t} - b_{t-1} \right] = c_t^g - x_t - \tau_t^L \tag{41}$$

Government tax revenues consist of taxes on wages and capital:

$$x_t = \tau_t^w w_t l_t + \tau_t^k \left[r_t^k u_t k_{t-1} + d_t \right] \tag{42}$$

Government consumption expenditures and lump-sum taxes evolve according to exogenous autoregressive processes

$$\log c_t^g = \rho_{cg} \log c_{t-1}^g + (1-\rho_{cg}) \log \bar{c}^g + \epsilon_t^{cg}, \tag{43}$$

$$\log \tau_t^L = \rho_L \log \tau_{t-1}^L + (1-\rho_L) \log \bar{\tau}^L + \epsilon_t^L, \tag{44}$$

where ϵ^{cg} and ϵ^L represent *i.i.d.* error terms.

The present paper's analysis focuses on policy feedback rules for taxes on capital income and labor income. To derive more elaborate policy rules, we first estimate the benchmark model closed with simple standard feedback rules (see e.g. Forni et al., 2009)

$$\log \tau_t^w = (1-\rho_w)\left(\log \bar{\tau}^w - \eta_w \log \bar{b}\right) + \rho_w \log \tau_{t-1}^w + (1-\rho_w)\,\eta_w \log b_{t-1} + \epsilon_{t,\tau^w}, \tag{45}$$

$$\log \tau_t^k = (1-\rho_k)\left(\log \bar{\tau}^k - \eta_k \log \bar{b}\right) + \rho_k \log \tau_{t-1}^k + (1-\rho_k)\,\eta_k \log b_{t-1} + \epsilon_{t,\tau^k}, \tag{46}$$

where ϵ_{t,τ^w} and ϵ_{t,τ^k} denote *i.i.d.* error terms.

Aggregation, Market Clearing, and Equilibrium

The formulation of sticky prices and wages implies inefficiencies and output losses relative to an economy with flexible prices in the goods and labor market. For this reason, we have to take the effects of price and wage dispersion into account when aggregating across firms and households (e.g. Schmitt-Grohé and Uribe, 2006). Following on from Schmitt-Grohé and Uribe (2006), we use the variable p_t^+ to capture the resource costs induced by inefficient price dispersion:

$$p_t^+ = (1-\gamma_p)\left(p_t^*\right)^{-\theta_p} + \gamma_p \left(\frac{\bar{\pi}}{\pi_t}\right)^{-\theta_p} p_{t-1}^+ \tag{47}$$

The resource constraint, i.e. equilibrium condition of the goods market, is then given by

$$\frac{\left(\left(u_t k_{t-1}\right)^{\alpha}\left(l_t^d \varepsilon_{z,t}\right)^{1-\alpha} - \Omega\right)}{p_t^+} = c_t + I_t + c_t^g + \phi_t\left(u_t\right) k_{t-1} \tag{48}$$

To take the loss in output caused by wage dispersion into account, we use the variable w_t^+, which is defined as:

$$w_t^+ = (1-\gamma_w)\left(w_t^*\right)^{-\theta_w} + \gamma_w \left(\frac{\bar{\pi}}{\pi_t^w}\right)^{-\theta_w} w_{t-1}^+ \tag{49}$$

The equilibrium condition of the labor market then becomes:

$$l_t = w_t^+ l_t^d \tag{50}$$

The dispersion of wages causes a dispersion in utility across households. This dispersion is measured by the variable $\tilde{w}_t^+$:

$$\tilde{w}_t^+ = (1-\gamma_w)\left(w_t^*\right)^{-\theta_w(1+\sigma_l)} + \gamma_w \left(\frac{\bar{\pi}}{\pi_t^w}\right)^{-\theta_w(1+\sigma_l)} \tilde{w}_{t-1}^+ \tag{51}$$

Finally, aggregated utility across households is:

$$U_t = \frac{\left(c_t - hc_{t-1}\right)^{1-\sigma_c}}{1-\sigma_c} - \psi_l \frac{\tilde{w}_t^+ \left(\frac{l_t}{w_t^+}\right)^{1+\sigma_l}}{1+\sigma_l} \tag{52}$$

The competitive equilibrium can now be defined as follows: A stationary competitive equilibrium is a set of stationary processes F_t^w, F_t^p, K_t^w, K_t^p, p_t^*, w_t^*, d_t, p_t^+, w_t^+, π_t^w, π_t, w_t, y_t, l_t, k_t, z_t, $\varepsilon_{i,t}$, $\varepsilon_{z,t}$, $\varepsilon_{q,t}$, s_t, ϕ_t, χ_t, I_t, c_t, u_t, r_t^k, l_t^d, b_t, x_t, R_t, τ_t^w, τ_t^k, τ_t^L, c_t^g satisfying equations (2) - (6), (8) - (12), (19) - (23), (28), (30) - (32), (36) - (50), given exogenous stochastic processes $\{\epsilon_t^i, \epsilon_t^q, \epsilon_t^z, \epsilon_t^{cg}, \epsilon_{t,\tau^k}, \epsilon_{t,\tau^w}, \epsilon_t^L, \epsilon_t^m, \}_{t=0}^\infty$, and the initial conditions $\varepsilon_{i,0}$, $\varepsilon_{z,0}$, $\varepsilon_{q,0}$, c_0^g, τ_0^L, τ_0^w, τ_0^k, R_{-1}, c_{-1}, I_{-1}, k_{-1}, p_{-1}^+, w_{-1}, w_{-1}^+, b_{-1}.

2.3 Data

As observable variables we employ private consumption, private investment, output, inflation, tax rates on capital and wages, public transfers, interest rates, and tax revenues. Since the model is not thought of as giving a precise description of tax revenues, we add a measurement error to the tax revenue observation equation. This leaves us with eight structural shocks incorporated in the model, and one measurement error, which correspond to the nine observable variables.

The time series are quarterly US data. A detailed description of the source can be found in appendix A. The tax rates are computed as in Jones (2002). Whenever necessary, the data are transformed into real terms and per capita.

Since the employed model does not exhibit an endogenous trend, we de-trend the data prior to the estimation. In contrast to most studies in the literature, we do not use a first-difference filter to de-trend the data, because it puts too much weight on high frequencies of the data. Instead, we employ a one-sided HP filter.[2] In contrast to the two-sided HP filter, the one-sided HP filter is not adversely affected by the correlation of data points with subsequent observations. The one-sided HP filter is implemented for each time series using an initialization window of 40 quarters. Figure 1 plots the raw time series data against the one-sided HP trend.

The complete data set ranges from 1958:1 to 2009:2. For the estimation procedure we employ only a sub-sample covering 1983:1 to 2008:4. We choose this particular sample for two reasons: first, to exclude the high-inflation period during the 1970s and the Volcker disinflation years, and second, because monetary policy is characterized by a Taylor rule (Taylor, 1993) and thought to be active, whereas fiscal policy is assumed to be passive (in the spirit of Leeper, 1991). All these assumptions are included in our model setup and by the subsequent prior choice.

2.4 Prior Choice and Calibrated Parameters

We calibrate the discount factor $\beta = 0.9926$ to yield a steady-state quarterly real interest rate of 1.25%. In order to match an investment-to-output ratio of 11.43% after taxes, we set the share of capital in production to $\alpha = 0.3$ and the depreciation rate of capital to $\delta = 0.025$. Similar to Schmitt-Grohé and Uribe (2004) the elasticities of substitution between intermediate goods θ_p and labor inputs θ_w are chosen so that the steady-state mark-up for prices and wages is 20% and 10%, respectively.

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[2] The filter is parameterized with $\lambda_{HP} = 1600$.

The steady-state ratio of government consumption expenditures to output $\bar{c}^g/\bar{y}$ and the steady-state ratio of lump-sum taxes to output $\bar{\tau}^L/\bar{y}$ is set to 18% and −7%, respectively. This implies a ratio of private consumption to output $\bar{c}/\bar{y}$ of approximately 60%. The steady-state value of annual inflation is calibrated as $\bar{\pi} = 1.0112$; the steady-state values for the tax rates on capital $\bar{\tau}^k = 0.3572$ and wages $\bar{\tau}^w = 0.2343$ are the averages of our time series. An overview of the calibrated values is given in Table 1.[3]

The remaining parameters are estimated. In general, we follow the most recent and widely accepted studies for our choice of the prior distributions (see e.g. Smets and Wouters, 2007; Christiano, Motto, and Rostagno, 2010). In some cases we deviate from that literature to allow for a slightly wider and less informative prior distribution. An overview of the employed prior distributions can be found in Table 2.

More precisely, we choose a Gamma distribution with a standard deviation of 0.5 and a mean of 1.5 and 2 for the inverse intertemporal elasticity of substitution and the inverse Frisch elasticity, respectively. These values are in line with Smets and Wouters (2007). The habit parameter is assumed to be Beta-distributed with mean 0.5 and a standard deviation of 0.15. For the investment adjustment cost parameter we specify a Gamma distribution with mean 4 and standard distribution 1.25.

The utilization costs are characterized by σ_u, which is estimated by Altig, Christiano, Eichenbaum, and Lindé (2010) to be 2.02. We therefore define a Gamma distribution centered around 2 with standard deviation 0.5. The Calvo probabilities for price and wage contracts are assumed to be Beta-distributed with mean 0.5 and a standard deviation of 0.15, implying an average duration of price and wage contracts of two quarters.

Since we employ the same fiscal policy rules as Forni et al. (2009), we also choose similar prior distributions for the parameters: The autoregressive coefficients are assumed to be Beta-distributed with mean 0.85 and a standard deviation of 0.1, and the coefficients on government debt are Gamma-distributed with mean 0.4 and a standard deviation of 0.2.

Concerning the monetary policy rule, we follow Christiano et al. (2010) in choosing a Beta distribution with mean 0.8 and a standard deviation of 0.1 for the interest rate

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[3] All tables are relegated to the appendix B.

smoothing coefficient, a Gamma distribution with mean 1.7 and standard deviation 0.1 for the policy coefficient on inflation, and a Normal distribution with mean 0.125 and standard deviation 0.05 for the policy coefficient on output. For the AR(1) coefficients of the shock processes we choose Beta distributions with mean 0.85 and standard deviation 0.1. The standard deviations of the structural shocks are assumed to be Inverse-Gamma distributed with mean 0.01 and 4 degrees of freedom.

2.5 Estimation Results for the Benchmark Model

In this section we present our estimation results for the benchmark model. The estimation results of the private sector's structural parameters and the monetary authority are essential to the following analysis. Therefore, we focus on discussing their estimates and juxtaposing them to the relevant study by Smets and Wouters (2007).

First, we estimate the posterior mode of the distribution and employ a random walk Metropolis-Hastings algorithm to approximate the distribution around the posterior mode. We run two chains, each with 1,000,000 parameter vectors draws. The first 90% have been discarded.[4]

Illustrations of the estimation results, i.e. prior vs. posterior distribution plots, can be found in Figure 2.[5] The plot indicates that the posterior distributions of all structural parameters are well approximated around the posterior mode. It also implies that all parameters, except the inverse of the Frisch elasticity, σ_l, are identified as substantially different from their prior distribution.[6] Table 3 provides detailed posterior statistics, e.g. posterior mean and the HPD interval of 10% and 90%. The posterior distributions of the parameters are similar to those obtained by Smets and Wouters (2007). In the following we focus on comparing our mode estimates to theirs.

The parameter estimates of associated with the households' preferences are well in line with the literature. The estimate of the inverse elasticity of the intertemporal substitution

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[4] Convergence statistics and further diagnostics are provided in the technical appendix on our websites.

[5] All figures are presented in appendix B of this paper.

[6] The difficulty in identifying the inverse of the Frisch elasticity, σ_l, stems from our choice of the observable variables, which leads to a rather flat likelihood as indicated by the check plots in the technical appendix.

,$\sigma_c = 1.59$, and the estimate of the inverse of the Frisch elasticity, $\sigma_l = 1.86$, are close to those obtained by Smets and Wouters (2007), $\sigma_c = 1.39, \sigma_l = 1.92$. The posterior mode of the habit parameter, $h = 0.48$, is lower than the estimate by Smets and Wouters (2007), 0.71, but higher than the estimate by Levin, Onatski, Williams, and Williams (2005), 0.29. While the capacity utilization cost $\sigma_u = 2.68$ is found to be higher than the value proposed by Altig et al. (2010), $\sigma_u = 2.02$, the estimate describing the investment adjustment cost $\nu = 4.48$ is lower than the value found by Smets and Wouters (2007), $\nu = 5.48$.

The estimates of the monetary policy rule are close to other studies in the literature: the interest rate-smoothing coefficient $\rho_r = 0.80$, the inflation coefficient $\rho_\pi = 1.77$ and the coefficient on output $\rho_y = 0.08$ are found inter alia by Smets and Wouters (2007).

The Calvo parameters of wage stickiness and price stickiness are estimated at $\gamma_w = 0.63$ and $\gamma_p = 0.58$, respectively. Both estimates are lower than the estimates of Smets and Wouters (2007), who estimate $\gamma_w = 0.73$ and $\gamma_p = 0.65$. Our estimates imply an average duration of wage and price contracts of approximately three and two quarters respectively.

The AR(1) coefficients of the shock processes are well identified like the standard deviations of the shock processes.

Figure 3 shows the plots of the historical data versus the smoothed estimates at the posterior mode. The tax revenue time series is well explained by the model, indicating that the measurement error is of minor importance.

Summarizing this subsection, we find that our estimation results are well identified and sufficiently close to other studies and therefore represent a good description of the private sector of the economy and a good starting point for the subsequent identification of fiscal policy rules.

3 Determination of Fiscal Policy Rules

We are interested in the feedback variables of simple rules that have the strongest impact on the variables of interest to the policymaker at the optimal allocation. In that respect, we compute the optimal allocation given the posterior estimates of the benchmark model's private sector. Section 3.2 summarizes the approximation of the optimal policy problem's highly non-linear solution with simple and linear rules. In Section 3.3 we describe calculation of the elasticities of variables' moments with respect to the feedback coefficients and choose the extended rules.

3.1 Optimal Policy

Given the structural estimates, we compute the optimal equilibrium of the economy described in section 2.2. We assume that the government has operated for an infinite number of periods and honors its commitments made in the past. This kind of policy under commitment is optimal from a timeless perspective (Woodford, 2003). The benevolent policymaker has two instruments, taxes on labor income and taxes on capital income.

Let N be the number of endogenous variables.[7] The optimal policy problem is defined as maximizing the lifetime expected utility

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left(c_t - hc_{t-1}, l_t\right), \tag{53}$$

where aggregate utility is defined by eq. (52), subject to the following $(N-2)$ equations (3), (4), (6), (8) - (12), (19) - (23), (30) - (32), (36) - (42), and (47)- (51).

The first-order conditions of the maximization problem yield $N + (N-2)$ equations for the N endogenous variables and $(N-2)$ Lagrangian multipliers associated with the private sector equilibrium constraints. The optimal equilibrium is then defined as a set of stationary variables F_t^w, F_t^p, K_t^w, K_t^p, p_t^*, w_t^*, d_t, p_t^+, w_t^+, π_t^w, π_t, w_t, y_t, l_t, k_t, z_t, $\varepsilon_{i,t}$, $\varepsilon_{z,t}$, $\varepsilon_{q,t}$, s_t, ϕ_t, χ_t, I_t, c_t, u_t, r_t^k, l_t^d, b_t, t_t, R_t, τ_t^L, τ_t^w, τ_t^k, c_t^g, $\tilde{w}_t^+$, and $N-2$ Lagrangian multipliers satisfying the first-order conditions of the optimal policy problem, as well as (2), (28), (5), (43), (44), given exogenous stochastic processes $\{\epsilon_t^i, \epsilon_t^q, \epsilon_t^z, \epsilon_t^{cg}, \epsilon_t^L, \epsilon_t^m\}_{t=0}^{\infty}$, values of the N endogenous variables dated $t < 0$, and values of the $(N-2)$ Lagrangian multipliers dated $t < 0$.

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[7] In our benchmark model the number of endogenous variables is $N = 30$.

When we compute the optimal policy, i.e. we solve for steady-state values of τ^k and τ^w, which solve the first-order conditions of the policymaker's maximization problem. The steady-states of the tax rates are $\bar{\tau}_k = -0.1259$ and $\bar{\tau}_w = 0.4281$. These numbers are in line to the values computed by Schmitt-Grohé and Uribe (2006). As in their approach, the social planner faces the following trade-off when setting the optimal tax rate for capital income and profits. On the one hand, she aims at eliminating the distortion between private and social returns on capital stemming from the price mark-up with a negative tax rate (see Judd, 2002). On the other hand, the social planner has an incentive to tax the profits with a high income tax. In the present model, the two opposite effects lead to a negative tax rate on capital and profits. To finance this subsidy and the given level of government consumption expenditures and transfers, the policymaker has to increase the tax rate on labor income.

The dynamic characteristics of the equilibrium, i.e. the impulse-response functions of some of the endogenous variables to exogenous shocks, are plotted as dashed lines in Figures 4 - 8. In general, the policymaker follows some particular principles when responding to an exogenous disturbance: to offset efficiency losses in the short-run and to finance the changes in the policy instrument, i.e. to balance the budget. This is nicely illustrated by the dynamic responses to an investment-specific shock (Figure 5). Investment drops and the tax on capital income is lowered.[8] The lower capital taxes are financed by an increase in taxes on wages. It is worth noting, in response to a technology shock (Figure 4), both tax rates respond pro-cyclically, that is they increase. Fiscal policy is thus conducted counter-cyclically. A closer look at the impulse-response functions shows clearly that an increase in investment is in general accompanied by an increase in the capital income tax rate. For taxes on labor income it seems that the responses of the real wage and hours worked determine the response of labor taxes. From this eyeball exercise, paired with some economic intuition, we expect that the coefficients on investment and hours worked or rather real wages should play an important role for approximating the optimal-policy dynamics by a linear feedback rules.

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[8] Keep in mind that the tax rate on capital income is negative in the steady state. An increase in the tax rate thus reduces subsidies.

To summarize, the computed optimal steady-state values for the tax on capital income and on labor income are in line with the literature. The dynamics around this steady-state are also in line with our expectation about optimal fiscal policy.

3.2 Approximation of Optimal Policy Rules by Linear Rules

In this section we describe the construction of the simple and linear rules for an approximation of the optimal policy.

Denote the set of variables the policymaker is interested in, or observable variables, by X^o. The observable variables are linked to the endogenous state variables X^z via the observation equation

$$X_t^o = HX_t^z. \tag{54}$$

The state variables evolve according to the state equation, which is the log-linearized solution of the model described in section 2.2

$$X_t^z = T(\theta^M)X_{t-1}^z + R(\theta^M)X_t^\epsilon, \tag{55}$$

where θ^M is a vector collecting the structural parameters of the model and X^ϵ the exogenous variables. We partition the vector into two sub-vectors: $\theta^M = [\theta^S \theta^P]$. The vector θ^S contains all the structural model parameters which are not included in the fiscal policy rules. The coefficients of the fiscal policy rules are included in the vector θ^P. In the benchmark model, the policy rules have been assumed to be eq. (45) and (46). Here, we define two very extensive rules, including a large variety of macroeconomic variables:

$$\tau_t^w = f\left(\tau_{t-1}^w, b_{t-1}, k_{t-1}, y_t, c_t, l_t, w_t, I_t, \pi_t, R_t\right) \text{ and} \tag{56}$$

$$\tau_t^k = f\left(\tau_{t-1}^k, b_{t-1}, k_{t-1}, y_t, c_t, l_t, w_t, I_t, \pi_t, R_t\right) \tag{57}$$

The vector of corresponding policy coefficients is

$$\theta^P = [\rho_w, \eta_{wk}, \eta_{wb}, \eta_{wy}, \eta_{wc}, \eta_{wl}, \eta_{wI}, \eta_{w\pi}, \eta_{ww}, \eta_{wR}, \\ \rho_k, \eta_{kk}, \eta_{kb}, \eta_{ky}, \eta_{kc}, \eta_{kl}, \eta_{kI}, \eta_{k\pi}, \eta_{kw}, \eta_{kR}], \tag{58}$$

where the two subscripts denote the tax instrument and their partial elasticities with respect to the feedback variables, respectively. To estimate θ^P, we fix θ^S at its posterior mode (see Section 2.5). Given the optimal allocation derived in Section 3.1, we simulate artificial time series. More precisely, we simulate data for output, private consumption, private investment, hours worked, and interest rates given a sequence of disturbances (ϵ_i, ϵ_z, ϵ_m, ϵ_q, ϵ_{cg}). The choice of the variables and shocks was motivated by the following considerations. The transfer shock, which is not included in the simulation, accounts for less than one percent of the variation in any of the variables in the subsequent analysis. Moreover, the choice of the variables is partly motivated by the remaining shocks in the model. The variables are further chosen because they constitute good indicators of the dynamic economic behavior. Moreover, we assume that if we are able to describe their dynamics we are also in a position to describe the dynamics of the remaining variables in the DSGE model. As it turns out, this assumption is valid. It is important to point out that, for the sensitivity analysis to determine the feedback coefficients later on, more variables are taken into account.

We use this time series to estimate the state system consisting of (55) and (54) by Bayesian model estimation. For the feedback coefficients we define diffuse prior distributions, that is a Normal distribution with mean zero and a standard deviation of five. The results of the posterior mode maximization can be found in Table 4.

In order to check whether the simple linear rules are indeed a good approximation of the optimal policy rules, we plot corresponding impulse-response functions as solid lines into Figures 4 - 8. The plots indicate that the simple rules approximate the optimal policy rules satisfactorily and justify our choice of variables ex post. In the next step, the estimated posterior distributions of the feedback parameters are employed to determine those feedback coefficients that have the most impact on the variables of interest to policymakers.

3.3 Computation of the Elasticities

We calculate the elasticities of the variables' moments with respect to the feedback coefficients employing the methodology proposed by Iskrev (2010). The methodology and our application are briefly summarized in this section.

The second moments[9] m of a set of observable variables X^o are the variance-covariance matrix $\Sigma_{m,0}$ and l autocovariances $(\Sigma_{m,1}, \ldots \Sigma_{m,l})$, which can be summarized in the vector $\Sigma_{m,L}$:

$$\Sigma_{m,L} = [vech(\Sigma_{m,0})', vec(\Sigma_{m,1})' \ldots vec(\Sigma_{m,l})']'. \tag{59}$$

The moments $\Sigma_{m,L}$ are calculated from the state space system defined by equations (55) and (54). The matrices T and R contain non-linear combinations, ς), of the structural parameter vector θ^M. In order to take into account the dependence of the moments $(\Sigma_{m,L})$ on the recursive law of motion (ς), which itself depends on structural parameters (θ^M), the Jacobian $J(L)$ is decomposed into two Jacobians

$$J(L) = J_1 J_2, \tag{60}$$

where J_1 contains the partial derivatives of the moments $\Sigma_{m,L}$ with respect to each recursive law of motion, and J_2 the partial derivatives of each recursive law of motion with respect to each parameter. Since we fix θ^S, we compute partial derivatives with respect to the 20 policy coefficients in θ^P only. We set $L = 1$, i.e. we consider one autocovariance and use DYNARE to compute the Jacobian $J(L)$. Afterwards, we multiply the partial derivatives by the policy coefficients and divide them by the corresponding moment to calculate the elasticities. To quantify the uncertainty, we take 2000 draws from the distribution of the policy coefficients derived in Section 3.2.

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[9] While the methodology proposed in Iskrev (2010) includes first moments of the data as well, we only consider second moments in our estimation. The steady state of the model simulating the data and the estimated model are identical.

In order to consider a wider variety of variables than the five observable variables, we compute the matrix $J(L)$ additionally for the real wage, capital, government debt, tax revenues, and inflation. The Tables 5 and 6 present the results. Moreover, the results are illustrated in Figures 9 and 10 for taxes on labor income and in Figures 11 and 12 for taxes on capital income, respectively. The plots show for each observable variable the box plot of the 75% quantile with respect to each policy coefficient.[10]

Inspecting the plots, we identify in each rule the autoregressive coefficient as most important to stabilize the variables of interest. In the labor tax rule the coefficient on hours worked, η_{wh}, exhibits the second highest elasticities. Two more coefficients seem to be important, η_{wI} and η_{wy}, the coefficients on investment and output, respectively. In order to keep the policy rules simple and straightforward to estimate, we only consider the more important of the two. Comparing lines four and eight in Table 5, we choose η_{wI} as the coefficient that displays a greater importance. Next to the autoregressive coefficient on capital income taxes, the coefficient on investment η_{kI} is most important. Besides these two, no other coefficient displays a high elasticity among all variables of interest.

In both rules, the coefficient on government debt is found to be of minor importance. This is not surprising, because no role for government debt is specified in the benchmark model. However, the coefficients might still be relevant empirically and are therefore included in the tax rules.

In summary, the new rules are specified as:

$$\hat{\tau}_t^w = \rho_w \hat{\tau}_{t-1}^w + (1-\rho_w)\left(\eta_{wb}\hat{b}_{t-1} + \eta_{wh}\hat{l}_t + \eta_{wI}\hat{i}_t\right) + \epsilon_{t,\tau^w} \tag{61}$$

$$\hat{\tau}_t^k = \rho_k \hat{\tau}_{t-1}^k + (1-\rho_k)\left(\eta_{kb}\hat{b}_{t-1} + \eta_{kI}\hat{i}_t\right) + \epsilon_{t,\tau^k} \tag{62}$$

In the remainder of this paper, we examine the empirical relevance of the above derived rules.

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[10] First we compute the Euclidian norm of the variance and the first autocovariance. The plots show elasticities scaled by the largest value for each observable variable thereafter.

4 Extended Economy

After deriving the new feedback rules, we estimate the benchmark model again; however, this time we use the newly derived tax rules (62) and (61) instead of the simple rules (46) and (45). This allows us to check for the policy invariance of the private sector estimates and to verify the empirical relevance of the feedback variables.

4.1 The Estimated Fiscal Policy Rules

The extended model is estimated given the data, the calibration, and the prior distribution presented in the subsections 2.3 and 2.4. The prior distribution of the smoothing parameter in the equations (61) and (62) is again specified as a Beta distribution with mean 0.85 and standard deviation 0.1. Similarly, the prior distribution for the coefficients on debt is a Gamma distribution with mean 0.4 and a standard deviation of 0.2. For the remaining policy coefficients we specify a prior which is normally distributed with mean 0 and standard deviation 1.

The model is estimated by running two random walk Metropolis-Hastings chains, each with 1,000,000 parameter vector draws. The first 90% are discarded. An overview of the posterior estimates is given in Table 7. Prior and posterior distributions are illustrated in Figure 13 and 14.

The posterior distributions of the structural parameters are, although not entirely identical, not much different to those presented in Section 2.5, either. Similar to the estimation results of the benchmark model, all posterior distributions of the parameters are different to the prior distribution, with the exception of the inverse of the Frisch elasticity σ_l.

The posterior modes of the parameters characterizing the preferences of the household are found to differ marginally:[11] $\sigma_c = 1.58 < 1.59$, $\sigma_l = 1.79 < 1.86$, and $h = 0.49 > 0.48$. While the parameters characterizing price stickiness, $\gamma_p = 0.58$, and investment adjustment costs, $\nu = 4.43 < 4.47$, are estimated similarly, the wage stickiness parameter

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[11] The following comparisons first report the estimate of the extended economy and then relate it to the estimate of the benchmark model.

is estimated higher, at $\gamma_w = 0.67 > 0.63$, and the capacity utilization costs at $\sigma_u = 2.61 < 2.68$. The latter display the largest differences.

The AR(1) coefficients of the shock processes and the standard deviation are estimated similarly too. Notable exceptions are the smaller standard deviations of the tax shocks. This follows directly from the larger systematic and endogenous tax rules employed in the estimation. Given these results, we can conclude that the private sector estimates are policy-invariant.

With respect to our estimated policy rules, we find that all feedback parameters are identified. Except for η_{wI}, the coefficients are also estimated different from zero. Both auto-regressive coefficients are estimated smaller than in the benchmark estimation: $\rho_k = 0.81 < 0.84$ and $\rho_w = 0.8 < 0.85$. The feedback coefficients on debt are also slightly smaller: $\eta_{wb} = 0.22 < 0.28$ and $\eta_{kb} = 0.2 < 0.24$. Thus, the relatively higher estimates are biased due to misspecified fiscal policy. The additional feedback coefficients that are estimated different from zero are $\eta_{kI} = 0.46$ and $\eta_{wh} = 1.33$, the feedback coefficient of capital income taxes on investment and the feedback coefficient of labor income taxes with respect to hours worked, respectively.

Thus, we find that the introduction of our feedback coefficients is empirically validated and that they reduce the non-systematic explanation for the fiscal policy sector. In the next section we investigate the effects in two dimensions. We analyze the characterization of fiscal policy and the effects on the historical shock decomposition of both tax rates.

4.2 Impulse Response Analysis

In order to further investigate the effects of the estimated policy rules, we calculate the resulting Bayesian impulse-response functions to the non-fiscal policy structural shocks of the model. Figures 18-21 display the results. The grey areas indicate the probability bands of the extended model's impulse response functions, while the dashed lines indicate the benchmark model's probability bands.

In line with the literature on fiscal policy we define a countercyclical fiscal policy as characterized by pro-cyclical tax rates relative to output. While η_{kI} introduces a counter-cyclical fiscal policy in the capital tax rule, the effect of η_{wh} on the labor tax rate is not so clear, since hours worked and output are not as highly correlated as investment and output.[12] The impulse-response functions suggest that the response of the tax rates are pro-cyclical, i.e. fiscal policy acts counter-cyclically. This is in sharp contrast to fiscal policy characterized by the simple rules of the benchmark model, which is mostly pro-cyclical. This finding is in line with Cúrdia and Reis (2010).

The difference between the policy rules becomes most apparent when comparing the effects of a risk-premium shock in Figure 19. Fiscal policy in the benchmark economy is pro-cyclical, driven by the positive response of government debt. In contrast, fiscal policy in the extended economy is counter-cyclical due to the negative response of investment and hours worked. An analogous picture is given by the impulse-response function to a monetary policy shock (Figure 21). While the benchmark economy would predict an increase in tax rates, the extended economy significantly estimates an initial decrease. For a technology shock (Figure 18) and an investment-specific shock (Figure 20) we find that capital income tax rates rise while labor tax rates do not show a significant behavior. The behavior of capital income tax rates is the opposite of what the benchmark economy would yield.

While the behavior of the private sector variables such as output, consumption, investment, hours worked, and the real wage is just slightly different for the different policy rules, the behavior of other fiscal variables such as tax revenues and government differs significantly. This corresponds to the counter-cyclical fiscal policy that takes into account larger government debt and lower tax revenues over a shorter horizon.

From this exercise we conclude that the estimation of the extended policy rules leads to a different characterization of the dynamic behavior of fiscal policy.

4.3 Smoothed Shocks and Historical Decomposition

The specified and estimated policy rules in the benchmark model and the extended model represent the systematic response of the fiscal authority to the state of the economy.

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[12] At the posterior model the correlations are 0.64 and 0.98 for the correlation of hours worked with output and investment and output respectively.

A misspecified rule will thus lead to misleading conclusions regarding the endogenous responses of the fiscal authority to the economy and may also overestimate the exogenous shocks to the policy instruments. In this section we investigate the two policy rules in those respects.

The first two sub-figures in Figure 15 display the smooth estimates for the capital income tax shock and the labor income tax shock. In these graphs the smooth shocks of the benchmark economy and the extended economy are plotted against each other. There is almost no difference between them. To test whether the identified exogenous changes make sense, we relate them to the identified policy shocks of Romer and Romer (2010). The shocks are shown in the third graph of Figure 15. Romer and Romer (2010) identify the tax shocks via a narrative record approach. For our comparison, the data was taken from the authors' website. The figure shows the calculation based on relative changes in liabilities to nominal GDP, including retroactive tax changes. The authors distinguish between exogenous tax shocks (black line) and endogenous tax changes (grey line). An exogenous tax shock is defined as decisions by the policymaker which are motivated by long-run considerations, i.e. to promote growth or to reduce the deficit. The 2001 and 2003 Bush tax cuts, motivated by expectation of increasing long-run growth, are one example.[13] Endogenous tax changes are defined by Romer and Romer (2010) as responses to the state of the economy. The authors find that such countercyclical motives were present for parts of the 2001 Bush tax cut and all of the post-September-11th cuts contained in the Job Creation and Worker Assistance Act of 2002, while during 1980s and 1990s such countercyclical actions were nonexistent. Comparing the identified shocks of the extended model with the identified shocks of Romer and Romer (2010), it becomes apparent that the model indeed identifies the correct shocks. The remaining changes in taxes do then indeed constitute systematic behavior of the fiscal authority to the state of the economy.

To further investigate the endogenous variation of the average tax rates, we examine their historical shock decomposition of each model economy. In Figure 17 and 16 we

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[13] In particular, these tax reforms are the Economic Growth and Tax Relief Reconciliation Act of 2001 and the Jobs and Growth Tax Relief Reconciliation Act of 2003.

plot the historical shock decomposition for the capital income tax rate and the labor income tax rate. Three main differences between the variance decomposition based on the estimates of the benchmark economy and the extended economy become apparent: first, in the extended economy less of the variance in the tax rates is explained by tax rate shocks (areas designed with left-sided lines). This result is not very surprising, since we have allowed for additional endogenous feedback. Closely related is the second difference. That is, the effects of the recessions as dated by the NBER, which are represented by the grey area, explain a larger portion of negative deviations from the steady state. This is especially the case for taxes on capital income after the recession in the beginning of the 1990s and the recession following 9/11.

Third, and most notably, the benchmark economy attributes only negative deviations from the trend to macroeconomic (non-policy) shocks (areas designed with right-sided lines). This is the case for both tax rates. The extended economy, on the other hand, attributes positive deviations due to macroeconomic shocks, too. For the capital income tax rate this is notably the time between 1984 and 1988, as well as the mid-1990s boom. In these times capital income was increasing, causing an increase in average capital income tax rates. For labor income tax rates we find that the boom in the mid-1980s contributed positively as well as that the shock associated with 9/11 explains a large part of the decrease in labor tax rates. Thus, our model with the extended policy rules takes due account of those endogenous adjustments and the effects of the recessions. We hence conclude that the extended policy rules constitute a better description of the fiscal sector's behavior than the simple rules of the benchmark model.

5 Conclusion

In this paper we present a new approach for determining fiscal feedback rules in an estimated DSGE model. We start by estimating a standard medium scale DSGE model to describe the behavior of the private sector. Considering the behavior of the government sector, we assume that the government responds to those variables in their feedback rules that influence a set of variables of interest to policymakers at the optimal allocation to the largest extent.

The feedback variables are determined at the optimal allocation. Given a sequence of exogenous shocks, we simulate time series for a set of variables that includes output, hours worked, private investment, the nominal interest rate, and private consumption. We are agnostic about the correct feedback variables in the policy rules. For this reason, we estimate simple linear policy rules for the tax rates to approximate the optimal dynamic behavior. The estimated policy rules are employed to compute the elasticities of variables' moments with respect to the feedback coefficients in the policy rule. The elasticities are calculated based on the approach proposed by Iskrev (2010). This allows us to rank the feedback variables according to their importance for the optimal dynamic behavior of the variables of interest to policymakers.

As an application of the innovative procedure, we specify the rule for the tax rate on labor and the tax rate on capital income. Both rules contain feedback coefficients on lagged tax rates, investment and government debt. In addition, a feedback coefficient on hours worked is important for the rule of labor income tax rates. All feedback coefficients, except for investment in the labor income tax rule, are identified significantly different from zero.

Our estimation results of the model with the evaluated tax rules imply two differences to the benchmark model. First, fiscal policy is characterized to act counter-cyclical. Second, the historical shock decomposition of average tax rates also attributes positive deviations from the steady state to macroeconomic shocks. This suggests that feedback rules derived with the proposed approach indeed help describe automatic stabilizing behavior better than in an estimated DSGE model with ad-hoc rules.

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A Data Description

The frequency of all final data used is quarterly.

Real GDP: This series is *BEA NIPA table 1.1.6 line 1.*

Nominal GDP: This series is *BEA NIPA table 1.1.5 line 1.*

Implicit GDP Deflator: The implicit GDP deflator is calculated as the ratio of nominal GDP to real GDP.

Private Consumption: This series is defined as private consumption of non-durable goods (*BEA NIPA table 1.1.5 line 5*) and private consumption of services (*BEA NIPA table 1.1.5 line 6*).

Private Investment: This series is gross private domestic investment (*BEA NIPA table 1.1.5 line 7*) plus private consumption of durable goods (*BEA NIPA table 1.1.5 line 4*).

Government Transfers: This series is defined as net current transfers, net capital transfers, and subsidies (*BEA NIPA table 3.2 line 32*). Whereas, net current transfers are current transfer payments (*BEA NIPA table 3.1 line 22*) minus current transfer receipts (*BEA NIPA table 3.2 line 15*), net capital transfers are defined as the difference between capital transfer payments (*BEA NIPA table 3.2 line 43*) and capital transfer receipts (*BEA NIPA table 3.2 line 39*).

Nominal Interest Rate: The quarterly nominal interest rate is defined as the the averages of daily figures of the fed funds fate obtained from the Board of Governors of the Federal Reserve System.

Inflation: The gross inflation rate is defined as the change in the implicit GDP deflator.

Population: This series is defined as civilian noninstitutional population (CNP16OV), age 16 and over provided by the U.S. Department of Labor: Bureau of Labor Statistics:

source: http://research.stlouisfed.org/fred2/series/CNP16OV?cid=104.

Tax Rates: Capital and labor tax rates are calculated following Jones (2002), where the labor tax rate is computed as:

$$\tau^w = \frac{FIT + SIT}{W + PRI/2 + CI} \cdot \frac{(W + PRI/2)}{EC + PRI/2} + \frac{CSI}{EC + PRI/2} \,,$$

where CSI denotes total contributions to social insurance (*BEA NIPA table 3.1 line 7*), EC denotes compensation of employees (*BEA NIPA table 1.12 line 2*), FIT denotes federal personal current taxes (*BEA NIPA table 3.2 line 3*), SIT denotes state and local personal current taxes (*BEA NIPA table 3.3 line 3*), PRI denotes proprietors' income (*BEA NIPA table 1.12 line 9*), W denotes wage and salary accruals (*BEA NIPA table 1.12 line 3*), and CI is capital income. Capital income is defined as rental income (*BEA NIPA table 1.12 line 12*), corporate profits (*BEA NIPA table 1.12 line 13*), interest income (*BEA NIPA table 1.12 line 18*), and $PRI/2$. The average capital income tax rate is computed as:

$$\tau^k = \frac{FIT + SIT}{W + PRI/2 + CI} \cdot \frac{CI}{CI + PT} + \frac{CT + PT}{CI + PT} \,,$$

where CT denotes taxes on corporate income (*BEA NIPA table 3.1 line 5*) and PT denotes property taxes (*BEA NIPA table 3.3 line 8*).

Government Tax Revenues: Tax revenues, x, are defined as the sum of capital income taxes and taxes on labor. They are computed as:

$$x = \tau^w \cdot (EC + PRI/2) + \tau^k \cdot (CI + PT) \,.$$

B Tables

Description	Symbol	Value
Discount factor	β	0.9926
Capital share	α	0.3
Depreciation rate	δ	0.025
Price markup	$\theta_p/(\theta_p-1)$	1.2
Wage markup	$\theta_w/(\theta_w-1)$	1.1
Annualized interest rate	$\bar{R}$	1.0418
Ratio of government consumption to output	$\bar{c}^g/\bar{y}$	0.18
Ratio of government transfers to output	$\bar{\tau}^l/\bar{y}$	-0.07
Steady-state capital tax rate	$\bar{\tau}_k$	0.3572
Steady-state labor tax rate	$\bar{\tau}_w$	0.2343

Table 1: Parameter calibration.

Parameter	Symbol	Domain	Density	Para(1)	Para(2)
Inv. intertemp. subst. elasticity	σ_c	$\mathbb{R}^+$	Gamma	1.75	0.5
Inverse Frisch elasticity	σ_l	$\mathbb{R}^+$	Gamma	2.0	0.5
Habit persistence	h	$[0,1)$	Beta	0.5	0.15
Calvo parameter prices	γ_p	$[0,1)$	Beta	0.5	0.15
Calvo parameter wages	γ_w	$[0,1)$	Beta	0.5	0.15
Investment adjustment cost	ν	$\mathbb{R}^+$	Gamma	4	1.25
Capital utilization cost	σ_u	$\mathbb{R}^+$	Gamma	2	0.5
Interest rate AR coefficient	ρ_R	$[0,1)$	Beta	0.8	0.1
Interest rate inflation coefficient	ρ_π	$\mathbb{R}^+$	Gamma	1.7	0.1
Interest rate output coefficient	ρ_y	$\mathbb{R}$	Gamma	0.125	0.05
Labor tax AR coefficient	ρ_w	$[0,1)$	Beta	0.85	0.1
Labor tax debt coefficient	η_{wb}	$\mathbb{R}^+$	Gamma	0.4	0.2
Capital tax AR coefficient	ρ_k	$[0,1)$	Beta	0.85	0.1
Capital tax debt coefficient	η_{kb}	$\mathbb{R}^+$	Gamma	0.4	0.2
Lump-sum tax AR coefficient	ρ_{τ^l}	$[0,1)$	Beta	0.85	0.1
Adjustment costs AR coefficient	ρ_i	$[0,1)$	Beta	0.85	0.1
Technology AR coefficient	ρ_z	$[0,1)$	Beta	0.85	0.1
Public consumption AR coefficient	ρ_{cg}	$[0,1)$	Beta	0.85	0.1
S.d. adjustment costs shock	ϵ_i	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. technology shock	ϵ_z	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. finance premium shock	ϵ_q	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. monetary policy shock	ϵ_m	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. wage tax shock	ϵ_{τ^w}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. capital tax shock	ϵ_{τ^k}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. lump-sum tax shock	ϵ_{τ^l}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. public consumption shock	ϵ_{cg}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. measurement error taxes	ϵ_{tax}	$\mathbb{R}^+$	InvGam	0.01	4.0

Table 2: Prior distribution of model parameters. Para(1) and Para(2) correspond to means and standard deviations for the Beta, Gamma, Inverted Gamma, and Normal distribution.

Parameter	Symbol	Mode	Mean	10%	90%
Inv. intertemp. subst. elasticity	σ_c	1.5932	1.6419	1.0484	2.2102
Inverse Frisch elasticity	σ_l	1.8663	1.9522	1.1264	2.7671
Habit persistence	h	0.4791	0.4867	0.3717	0.5978
Price stickiness	γ_p	0.5764	0.5868	0.5006	0.6778
Wage stickiness	γ_w	0.6268	0.6202	0.5178	0.7292
Investment adjustment cost	ν	4.4756	5.0134	3.0526	6.8946
Capital utilization cost	σ_u	2.6778	2.7955	2.0049	3.6010
Interest rate AR coefficient	ρ_R	0.7991	0.7997	0.7594	0.8397
Inflation coefficient	ρ_π	1.7737	1.7799	1.6174	1.9354
Output coefficient	ρ_y	0.0809	0.0858	0.0423	0.1295
Labor tax AR coefficient	ρ_w	0.8501	0.8500	0.7656	0.9371
Labor tax debt coefficient	η_{wb}	0.2770	0.3764	0.1471	0.6097
Capital tax AR coefficient	ρ_k	0.8425	0.8437	0.7687	0.9212
Capital tax debt coefficient	η_{kb}	0.2414	0.3340	0.0912	0.5735
Lump-sum tax AR coefficient	ρ_{τ^l}	0.7592	0.7582	0.6574	0.8583
Adjustment costs AR coefficient	ρ_i	0.4821	0.4950	0.3620	0.6246
Technology AR coefficient	ρ_z	0.9545	0.9320	0.8817	0.9881
Risk premium AR coefficient	ρ_q	0.8330	0.8172	0.7429	0.8928
Public consumption AR coefficient	ρ_{cg}	0.7838	0.7857	0.6877	0.8859
S.d. adjustment costs shock	ϵ_i	0.0279	0.0288	0.0244	0.0334
S.d. technology shock	ϵ_z	0.0057	0.0063	0.0047	0.0078
S.d. risk premium shock	ϵ_q	0.0038	0.0044	0.0026	0.0061
S.d. monetary policy shock	ϵ_m	0.0015	0.0016	0.0014	0.0018
S.d. labor tax shock	ϵ_{τ^w}	0.0216	0.0220	0.0194	0.0246
S.d. capital tax shock	ϵ_{τ^k}	0.0241	0.0244	0.0215	0.0271
S.d. lump-sum tax shock	ϵ_{τ^l}	0.0238	0.0242	0.0213	0.0269
S.d. public consumption shock	ϵ_{cg}	0.0156	0.0159	0.0141	0.0178
S.d. measurement error taxes	ϵ_{tax}	0.0100	0.0101	0.0090	0.0113
Log data density		3131.84	3132.25		

Table 3: Posterior mode and posterior distribution of the benchmark model's parameters.

Feedback Parameter	Symbol	Mode	S.d.	T-value
TAX RATE ON LABOR INCOME				
Labor tax rate	ρ_w	0.7535	0.0964	7.8131
Capital	η_{wk}	0.1409	0.2566	0.5492
Debt	η_{wb}	0.0244	0.0258	0.9450
Output	η_{wy}	-1.5314	2.7441	0.5581
Consumption	η_{wc}	-0.1640	1.0635	0.1542
Hours worked	η_{wh}	-2.9232	2.8044	1.0424
Wage rate	η_{ww}	0.4182	2.8895	0.1447
Investment	η_{wI}	0.5481	0.4745	1.1552
Inflation	$\eta_{w\pi}$	-1.7559	4.3417	0.4044
Nominal interest rate	η_{wR}	-0.3907	2.8738	0.1360
TAX RATE ON CAPITAL INCOME				
Capital tax rate	ρ_k	0.9029	0.0235	38.4078
Capital	η_{kk}	2.2929	2.8533	0.8036
Debt	η_{kb}	0.2407	0.2640	0.9117
Output	η_{ky}	-3.4380	4.6148	0.7450
Consumption	η_{kc}	-3.9752	4.3635	0.9110
Hours worked	η_{kh}	-5.6239	4.0358	1.3935
Wage rate	η_{kw}	6.4055	3.9973	1.6025
Investment	η_{kI}	-4.8572	2.0548	2.3638
Inflation	$\eta_{k\pi}$	3.1679	5.0700	0.6248
Nominal interest rate	η_{kR}	-0.3079	4.9389	0.0623

Table 4: Posterior mode maximization of optimized feedback coefficients.

Parameter	Symbol	$\hat{c}_t$	$\hat{y}_t$	$\hat{I}_t$	$\hat{R}_t$	$\hat{l}_t$	$\hat{w}_t$	$\hat{k}_t$	$\hat{b}_t$	$\hat{x}_t$	$\hat{\pi}_t$
Labor tax rate	ρ_w	0.3278 [.055;2.10]	0.4091 [.117;2.62]	0.4003 [.115;2.74]	1.4598 [.202;6.57]	0.5424 [.135;3.19]	0.9468 [.254;4.09]	1.6945 [.281;7.34]	2.0614 [.364;8.36]	1.6643 [.241;7.12]	1.7953 [.370;8.07]
Capital	η_{wk}	0.0271 [.006;.090]	0.0118 [.003;.061]	0.0152 [.004;.075]	0.0578 [.014;.224]	0.0138 [.003;.078]	0.0608 [.017;.220]	0.0868 [.022;.258]	0.1012 [.031;.303]	0.0572 [.015;.205]	0.0758 [.021;.249]
Debt	η_{wb}	0.0445 [.016;.092]	0.0213 [.009;0.062]	0.0173 [.006;.051]	0.0884 [.024;.280]	0.0176 [.006;.070]	0.1340 [.041;.370]	0.1240 [.044;.339]	0.2213 [.091;.496]	0.1000 [.030;.310]	0.2219 [.095;.466]
Output	η_{wy}	0.1909 [.060;0.546]	0.1453 [.055;0.490]	0.2401 [.107;.627]	0.2669 [.083;1.12]	0.2598 [.106;.683]	0.2724 [.069;.923]	0.5580 [.212;1.28]	0.3947 [.117;1.15]	0.3031 [.087;1.16]	0.3410 [.085;1.13]
Consumption	η_{wc}	0.1166 [.046;.279]	0.0216 [.005;.118]	0.0656 [.021;.194]	0.1160 [.025;.477]	0.0606 [.020;.195]	0.1742 [.049;.497]	0.2016 [.058;.577]	0.2189 [.057;.556]	0.1275 [.028;.486]	0.1697 [.053;.510]
Hours worked	η_{wh}	0.3418 [.068;0.978]	0.3256 [.072;1.072]	0.4081 [.109;1.16]	0.6941 [.170;2.05]	0.6057 [.188;1.50]	0.5668 [.184;1.75]	1.0204 [.256;2.60]	0.9156 [.263;2.76]	0.7262 [.220;2.29]	1.2157 [.437;2.70]
Wage rate	η_{ww}	0.1192 [.039;.364]	0.0576 [.012;.326]	0.0679 [.020;.329]	0.3736 [.114;1.11]	0.1414 [.041;.495]	0.4209 [.145;1.06]	0.4491 [.131;1.30]	0.4063 [.111;1.30]	0.4253 [.123;1.37]	0.5318 [.174;1.32]
Investment	η_{wI}	0.1364 [.047;0.409]	0.2060 [.097;0.553]	0.2462 [.122;.574]	0.3713 [.145;1.13]	0.2741 [.134;.678]	0.2742 [.099;.813]	0.5712 [.225;1.36]	0.8008 [.305;1.73]	0.3370 [.128;1.00]	0.5639 [.203;1.39]
Inflation	$\eta_{w\pi}$	0.0271 [.008;.099]	0.0218 [.007;.075]	0.0279 [.009;.090]	0.1290 [.050;.299]	0.0434 [.016;.110]	0.0753 [.021;.236]	0.0903 [.025;.307]	0.0791 [.022;.285]	0.1236 [.052;.308]	0.0902 [.023;.303]
Interest rate	η_{wR}	0.0217 [.007;0.071]	0.0151 [.005;0.048]	0.0195 [.007;0.058]	0.1318 [.050;.284]	0.0308 [.012;.074]	0.0459 [.011;.170]	0.0590 [.017;.185]	0.0579 [.015;.180]	0.1295 [.046;.299]	0.0637 [.016;.196]

Table 5: Elasticity of variables' moments with respect to the feedback coefficients of the labor income tax rule.

Parameter	Symbol	$\hat{c}_t$	$\hat{y}_t$	$\hat{I}_t$	$\hat{R}_t$	$\hat{l}_t$	$\hat{w}_t$	$\hat{k}_t$	$\hat{b}_t$	$\hat{x}_t$	$\hat{\pi}_t$
Capital tax rate	ρ_k	0.4948 [.174;1.62]	1.4710 [.796;2.75]	2.5562 [1.73;3.64]	0.8600 [.339;3.55]	1.6460 [.960;2.72]	0.7535 [.374; 2.77]	0.0964 [1.46;4.72]	7.8131 [.606;4.52]	0.0964 [.363;4.15]	7.8131 [.440;3.44]
Capital	η_{kk}	0.0236 [.008;.078]	0.0148 [.005;.045]	0.0148 [.005;.045]	0.0381 [.008;.169]	0.0126 [.005;.048]	0.7535 [.021;.297]	0.0964 [.014;.209]	7.8131 [.037;.396]	0.0964 [.008;.193]	7.8131 [.012;.210]
Debt	η_{kb}	0.0445 [.013;.106]	0.0139 [.004;.031]	0.0185 [.005;.042]	0.0340 [.011;.106]	0.0174 [.006;.041]	0.7535 [.042;.342]	0.0964 [.017;.173]	7.8131 [.028;.277]	0.0964 [.013;.139]	7.8131 [.024;.209]
Output	η_{ky}	0.0525 [.019;.128]	0.0504 [.021;.105]	0.0454 [.017;.104]	0.0314 [.008;.145]	0.0336 [.011;.087]	0.7535 [.041;.279]	0.0964 [.039;.234]	7.8131 [.026;.212]	0.0964 [.007;.139]	7.8131 [.010;.151]
Consumption	η_{kc}	0.0812 [.029;.252]	0.0237 [.008;.062]	0.0213 [.007;.070]	0.0499 [.010;.181]	0.0204 [.005;.066]	0.7535 [.071;.544]	0.0964 [.020;.225]	7.8131 [.027;.300]	0.0964 [.012;.207]	7.8131 [.015;.214]
Hours worked	η_{kh}	0.0500 [.013;.165]	0.0504 [.020;.132]	0.0551 [.025;.130]	0.0663 [.015;.233]	0.0507 [.020;.121]	0.7535 [.036;.419]	0.0964 [.043;.286]	7.8131 [.037;.343]	0.0964 [.020;.266]	7.8131 [.029;.306]
Wage rate	η_{kw}	0.0403 [.015;.092]	0.0187 [.005;.052]	0.0162 [.005;.048]	0.0675 [.022;.193]	0.0210 [.008;.054]	0.7535 [.037;.306]	0.0964 [.026;.220]	7.8131 [.034;.336]	0.0964 [.021;.223]	7.8131 [.025;.247]
Investment	η_{kI}	0.0919 [.039;.226]	0.1694 [.097;.319]	0.1398 [.079;.272]	0.1240 [.034;.417]	0.1186 [.065;.262]	0.7535 [.099;.573]	0.0964 [.164;.745]	7.8131 [.241;.915]	0.0964 [.036;.462]	7.8131 [.075;.654]
Inflation	$\eta_{k\pi}$	0.0041 [.001;.012]	0.0026 [.001;.007]	0.0042 [.001;.010]	0.0069 [.001;.024]	0.0035 [.001;.008]	0.7535 [.003;.038]	0.0964 [.002;.024]	7.8131 [.002;.026]	0.0964 [.002;.028]	7.8131 [.001;.023]
Interest rate	η_{kR}	0.0045 [.001;.012]	0.0036 [.001;.008]	0.0022 [.001;.008]	0.0086 [.002;.026]	0.0028 [.001;.008]	0.7535 [.003;.034]	0.0964 [.002;.024]	7.8131 [.003;.028]	0.0964 [.002;.028]	7.8131 [.002;.023]

Table 6: Elasticity of variables' moments with respect to the feedback coefficients of the capital income tax rule.

Parameter	Symbol	Mode	Mean	10%	90%
Inv. intertemp. subst. elasticity	σ_c	1.5787	1.6634	1.0530	2.2566
Inverse Frisch elasticity	σ_l	1.7939	1.9383	1.0926	2.6917
Habit persistence	h	0.4945	0.4937	0.3792	0.6138
Price stickiness	γ_p	0.5820	0.5954	0.5098	0.6814
Wage stickiness	γ_w	0.6714	0.6489	0.5384	0.7611
Investment adjustment cost	ν	4.4309	4.8865	2.9242	6.8783
Capital utilization cost	σ_u	2.6122	2.7508	1.9297	3.5514
Interest rate AR coefficient	ρ_R	0.8012	0.8009	0.7610	0.8411
Inflation coefficient	ρ_π	1.7643	1.7770	1.6201	1.9362
Output coefficient	ρ_y	0.0841	0.0869	0.0407	0.1297
Labor tax AR coefficient	ρ_w	0.8025	0.8367	0.7462	0.9375
Labor tax debt coefficient	η_{wb}	0.2184	0.3314	0.1250	0.5624
Labor tax labor coefficient	η_{wh}	1.3260	1.2509	-0.0524	2.6063
Labor tax investment coefficient	η_{wI}	-0.0114	0.0239	-0.4201	0.4548
Capital tax AR coefficient	ρ_k	0.8079	0.8284	0.7436	0.9135
Capital tax debt coefficient	η_{kb}	0.1968	0.2680	0.0691	0.4669
Capital tax investment coefficient	η_{kI}	0.4633	0.5055	0.0922	0.8980
Lump-sum tax AR coefficient	ρ_{τ^l}	0.7589	0.7578	0.6554	0.8553
Adjustment costs AR coefficient	ρ_i	0.4856	0.4933	0.3743	0.6192
Technology AR coefficient	ρ_z	0.9491	0.9343	0.8853	0.9857
Risk premium AR coefficient	ρ_q	0.8460	0.8295	0.7558	0.9014
Public consumption AR coefficient	ρ_{cg}	0.7795	0.7809	0.6868	0.8792
S.d. adjustment costs shock	ϵ_i	0.0288	0.0296	0.0250	0.0342
S.d. technology shock	ϵ_z	0.0058	0.0064	0.0048	0.0079
S.d. risk premium shock	ϵ_q	0.0036	0.0042	0.0025	0.0059
S.d. monetary policy shock	ϵ_m	0.0015	0.0016	0.0014	0.0017
S.d. labor tax shock	ϵ_{τ^w}	0.0209	0.0216	0.0191	0.0242
S.d. capital tax shock	ϵ_{τ^k}	0.0234	0.0239	0.0211	0.0265
S.d. lump-sum tax shock	ϵ_{τ^l}	0.0238	0.0242	0.0214	0.0269
S.d. public consumption shock	ϵ_{cg}	0.0147	0.0150	0.0133	0.0166
S.d. measurement error taxes	ϵ_{tax}	0.0099	0.0101	0.0090	0.0112
Log data density		3133.58	3134.11		

Table 7: Posterior distribution of the extended model's parameters.

C Figures

C.1 Benchmark Model

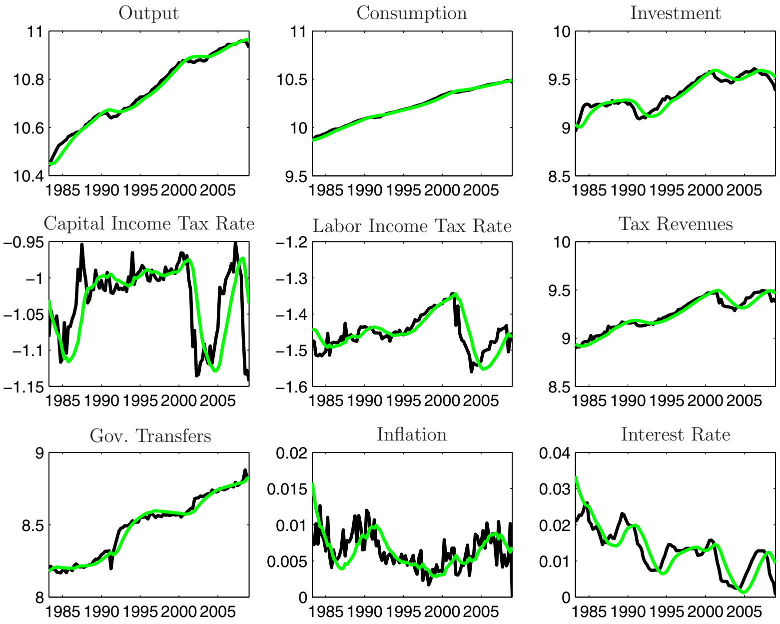


Figure 1: Raw time series (black) and and corresponding trend (green).

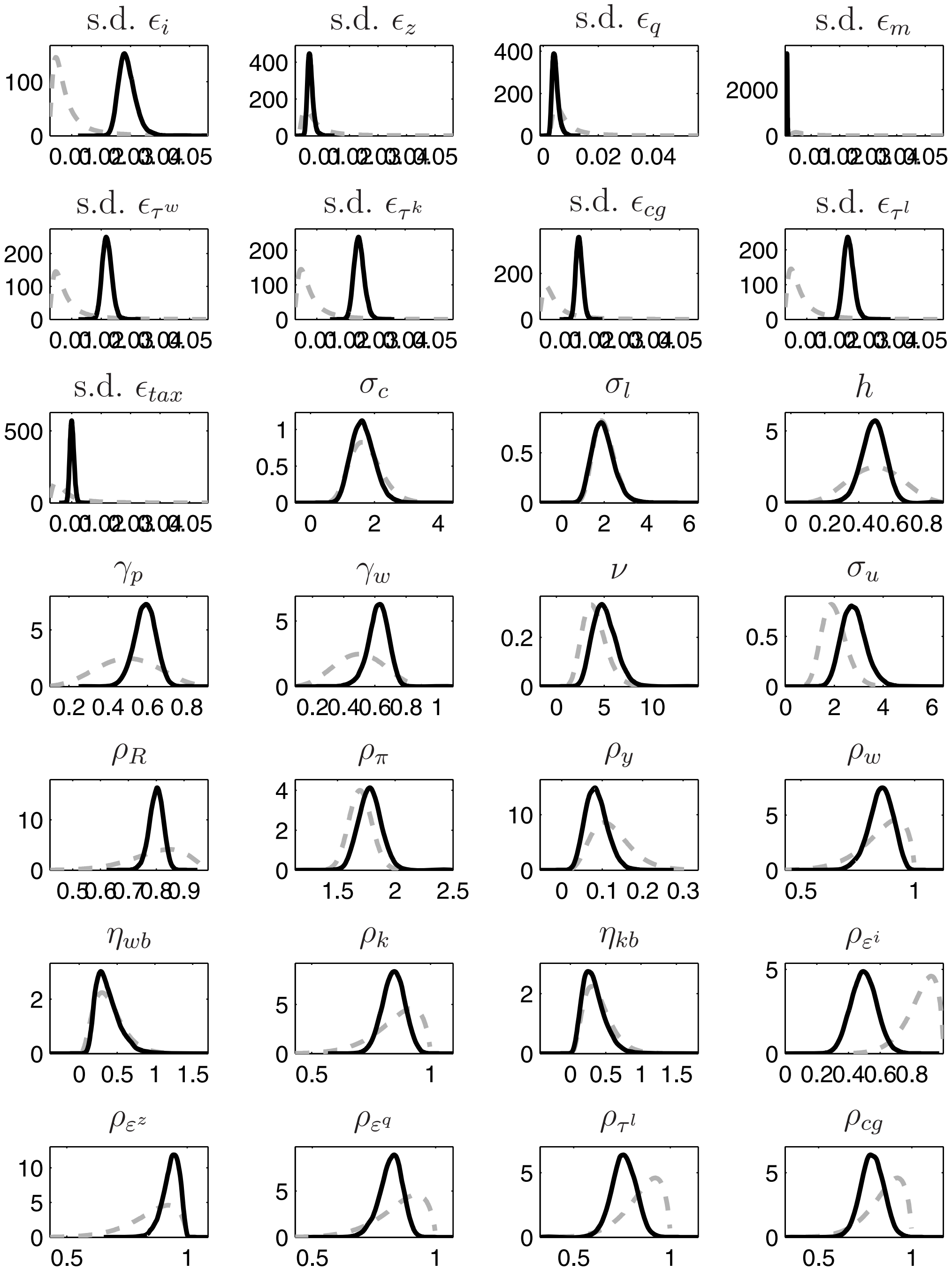


Figure 2: Prior (grey dashed) and posterior (black solid) distribution of the benchmark model's parameters.

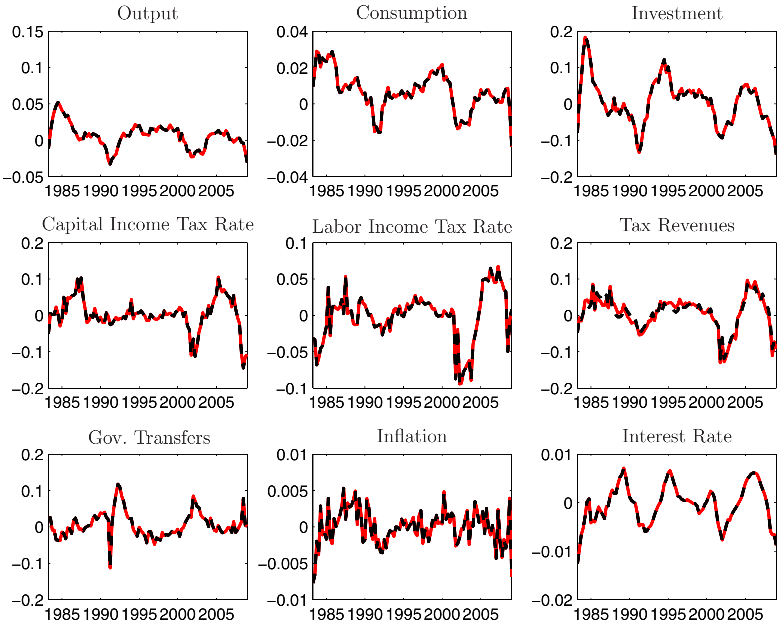


Figure 3: Historical variables (red) and smoothed variables (black) at posterior mode.

C.2 Determination of Policy Rules

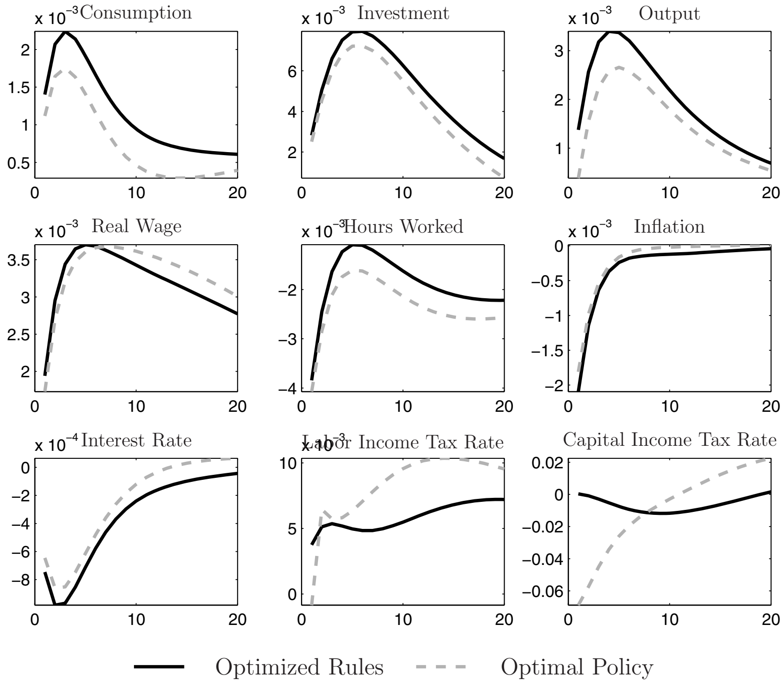


Figure 4: Impulse responses under optimized rules (solid) and optimal policy (dashed). Technology shock.

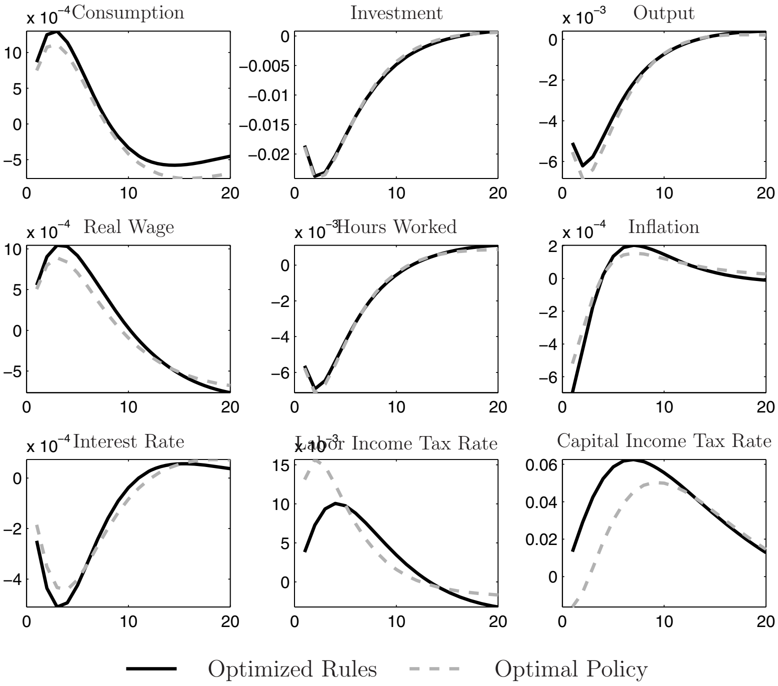


Figure 5: Impulse responses under optimized rules (solid) and optimal policy (dashed). Investment-specific shock.

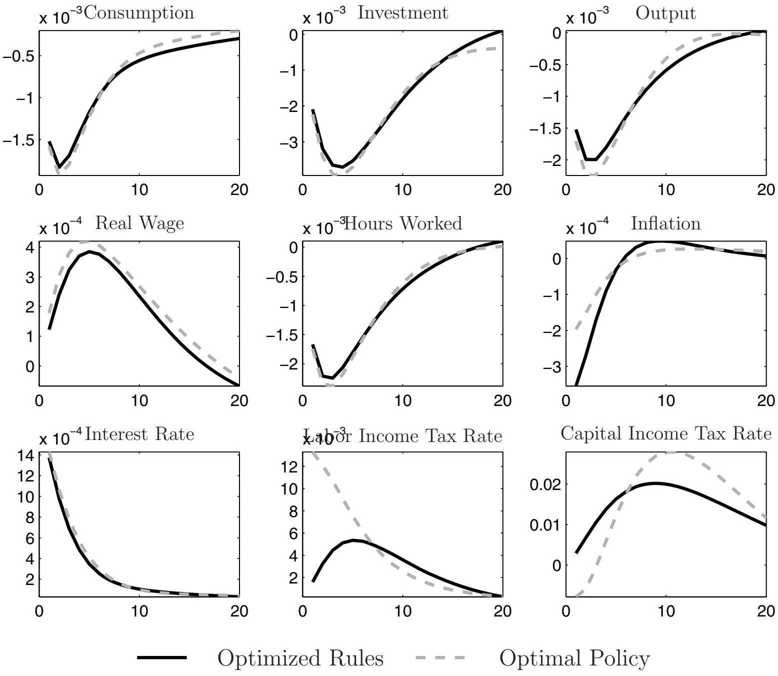


Figure 6: Impulse responses under optimized rules (solid) and optimal policy (dashed). Monetary policy shock.

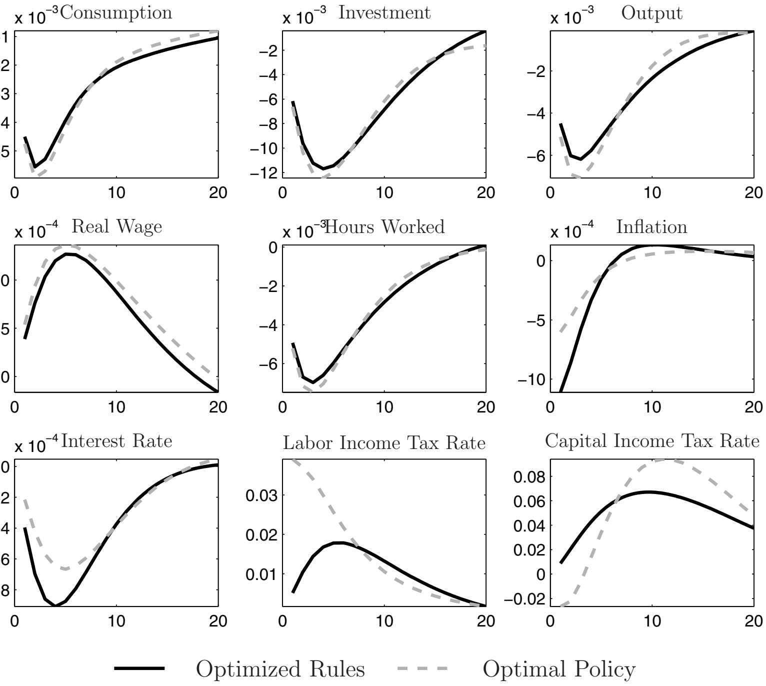


Figure 7: Impulse responses under optimized rules (solid) and optimal policy (dashed). Risk premium shock.

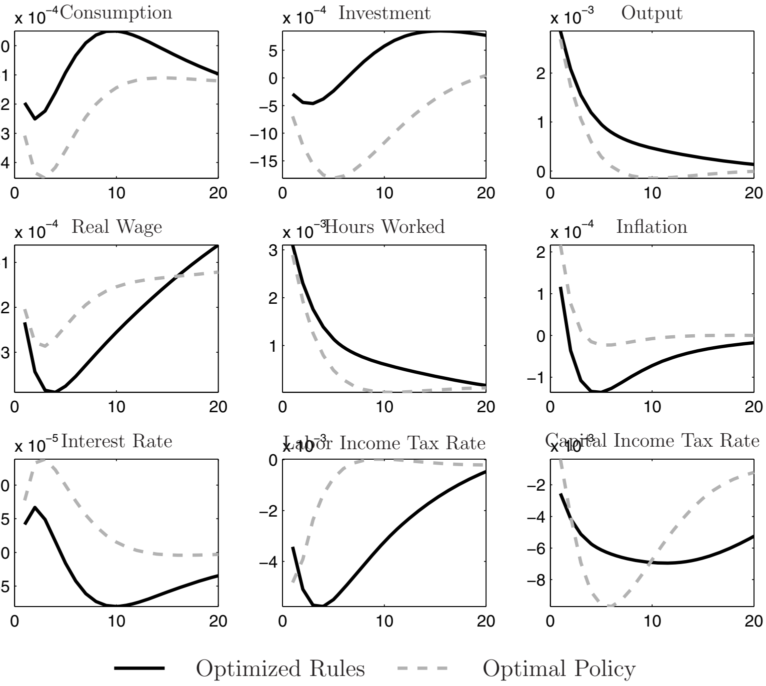


Figure 8: Impulse responses under optimized rules (solid) and optimal policy (dashed). Government consumption shock.

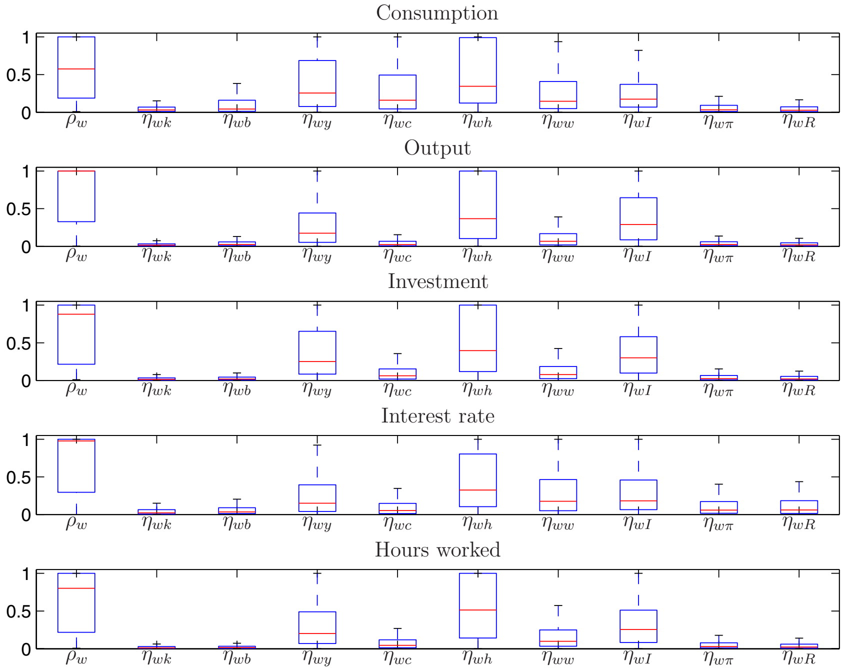


Figure 9: Relative elasticity of variables' moments with respect to feedback paramters of the labor income tax rule.

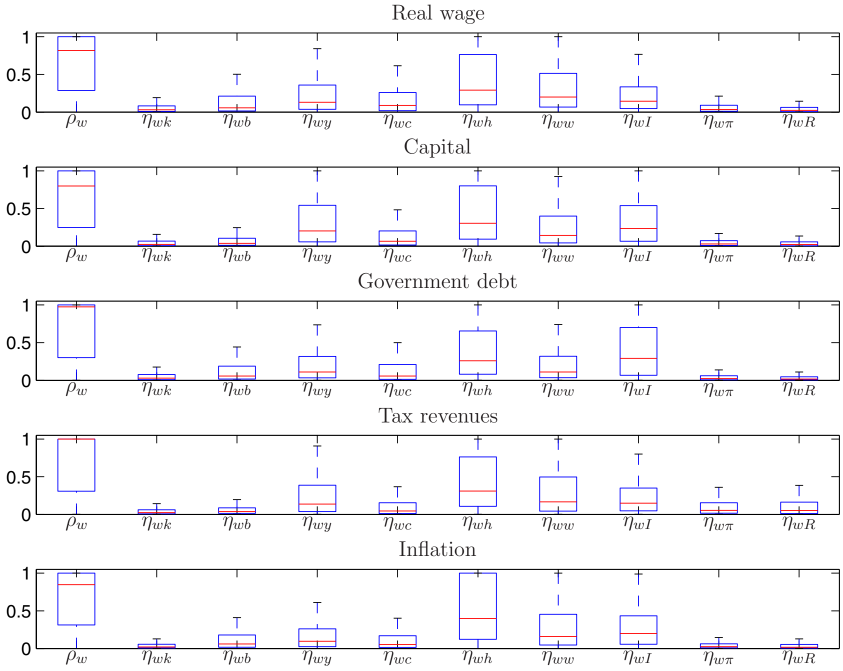


Figure 10: Relative elasticity of variables' moments with respect to feedback paramters of the labor income tax rule.

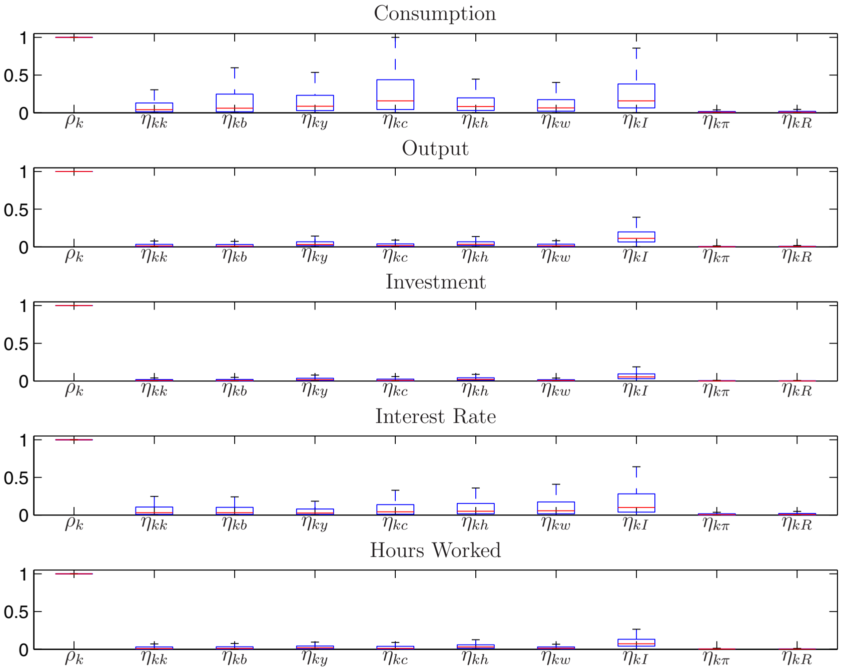


Figure 11: Relative elasticity of variables' moments with respect to feedback paramters of the capital income tax rule.

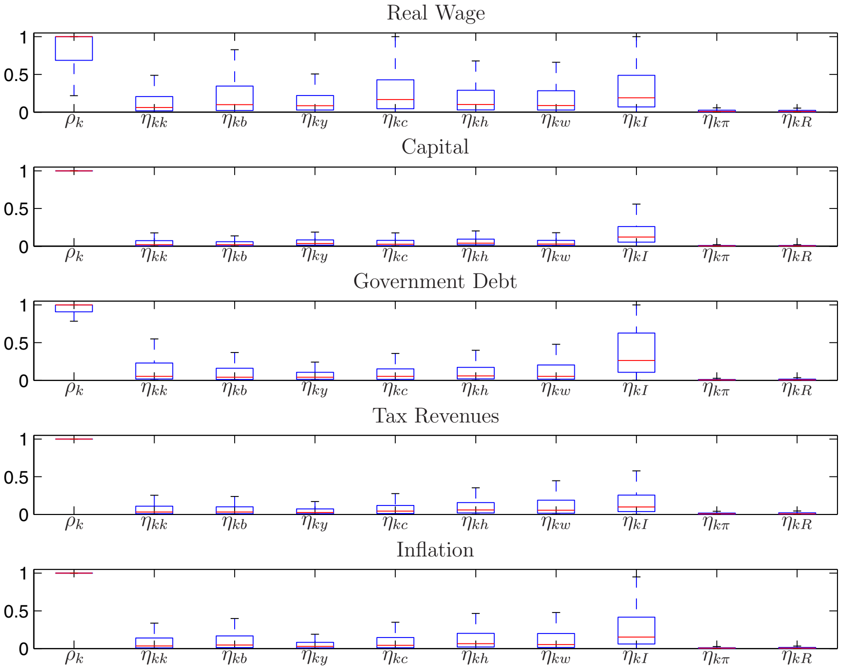


Figure 12: Relative elasticity of the moments of various variables with respect to feedback paramters of the capital income tax rule.

C.3 Extended Economy

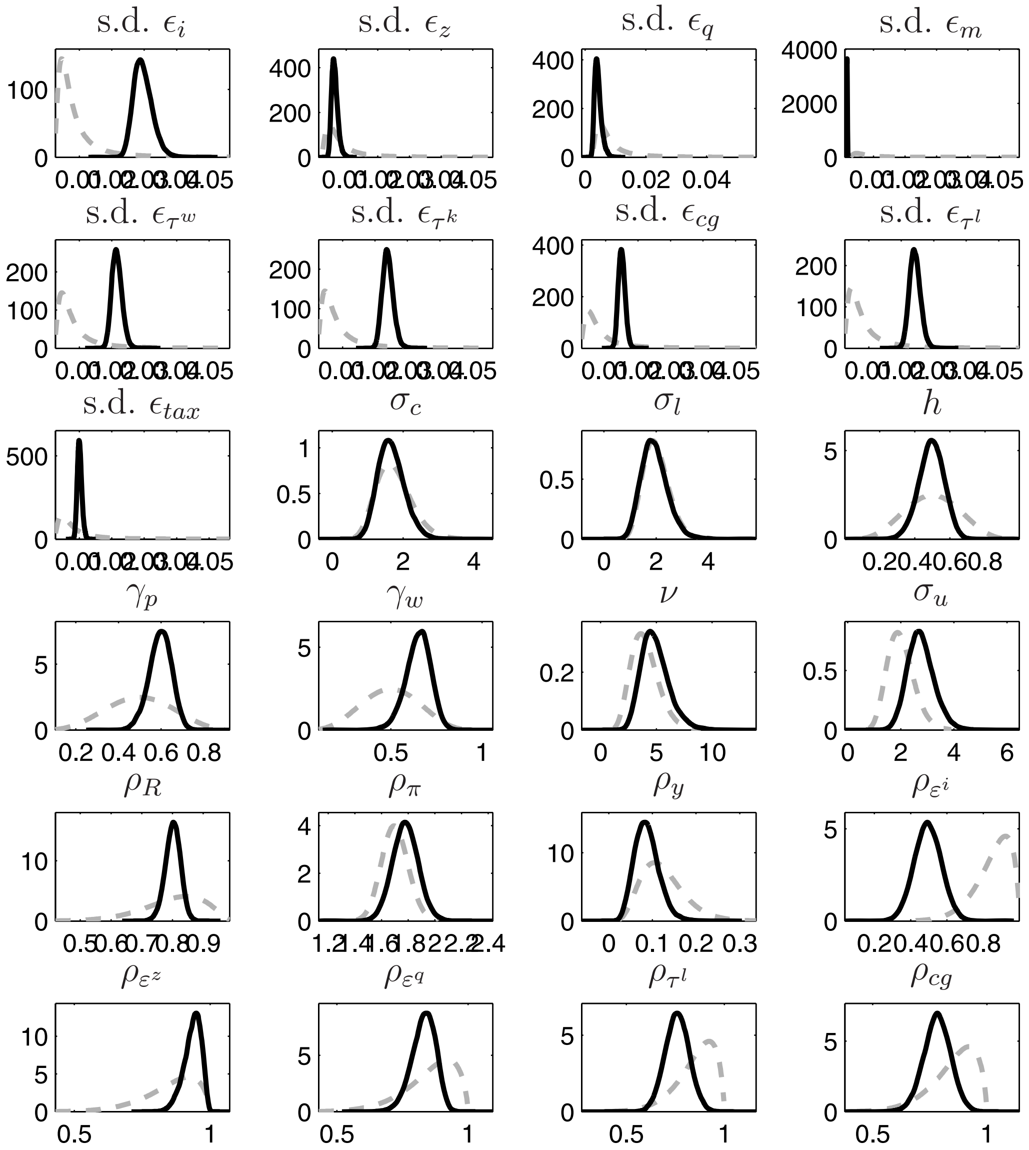


Figure 13: Prior (grey dashed) and posterior (black solid) distribution for the extended model.

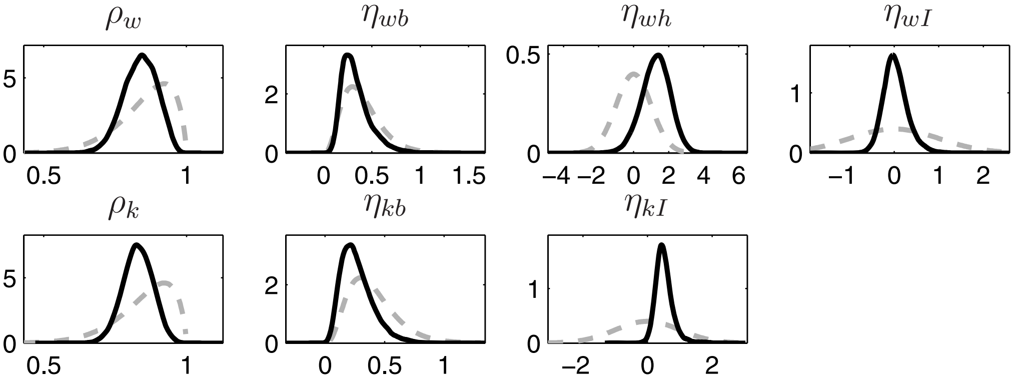


Figure 14: Prior (grey dashed) and posterior (black solid) distribution for the extended model.

C.4 Extended vs. Benchmark Economy

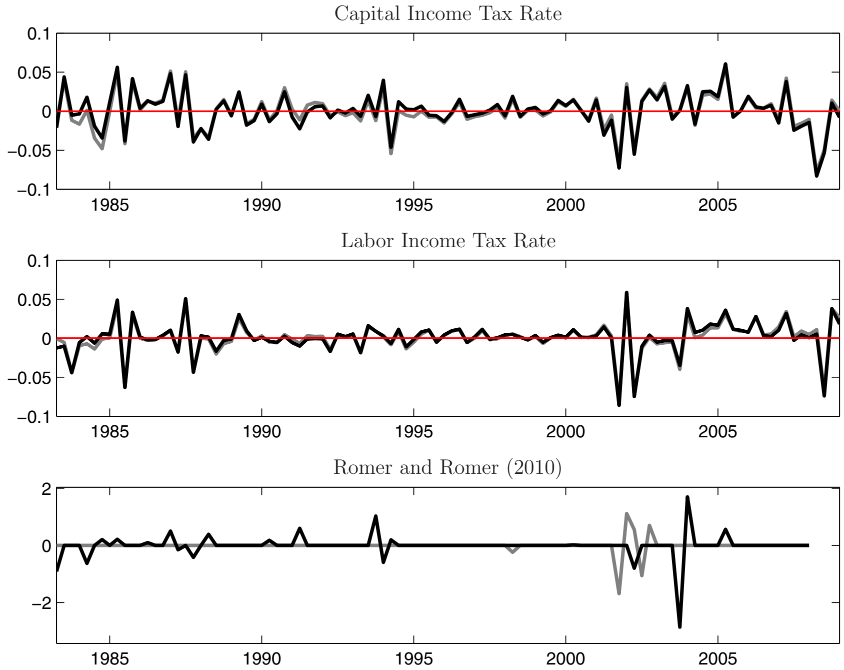
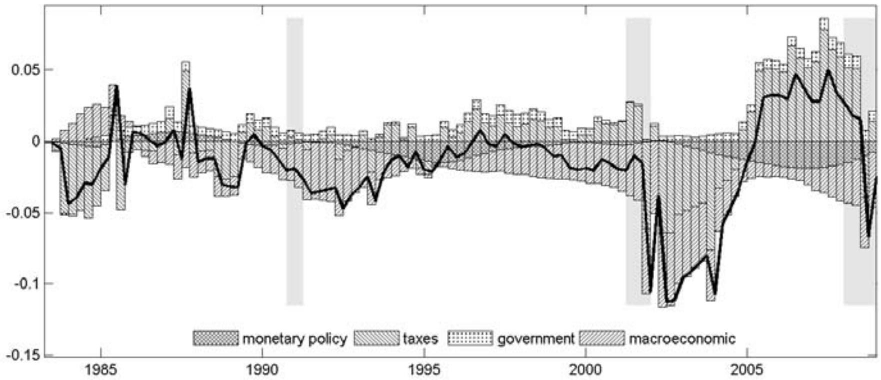
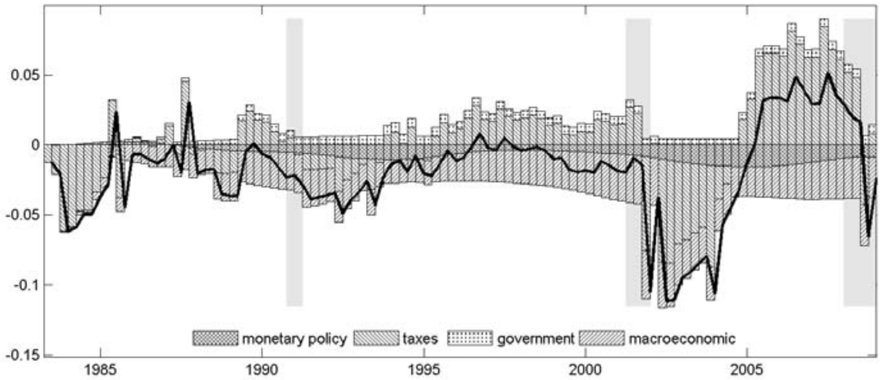


Figure 15: Identified tax shocks of the estimated model and the tax shocks identified by Romer and Romer (2010).

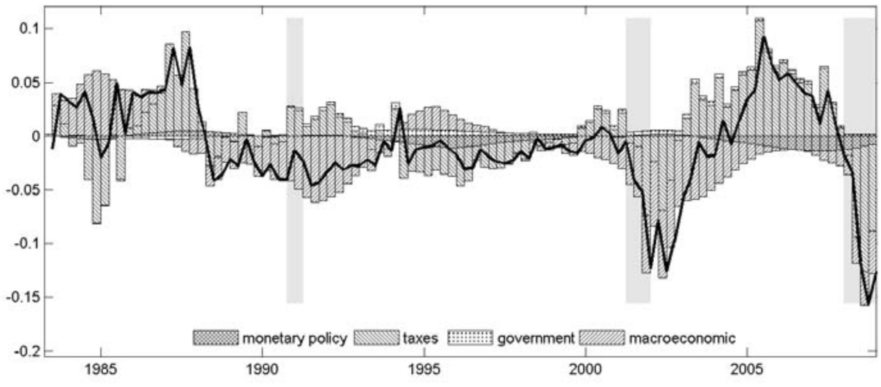


(a) New feedback rule.

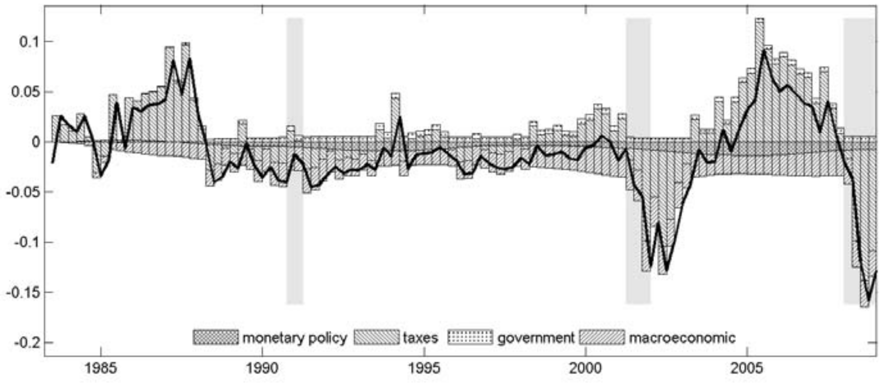


(b) Old feedback rule.

Figure 16: Historical decomposition of the observed labor income tax rate. The grey areas represent NBER recessions.



(a) New feedback rule.



(b) Old feedback rule.

Figure 17: Historical decomposition of the observed capital income tax rate. The grey areas represent NBER recessions.

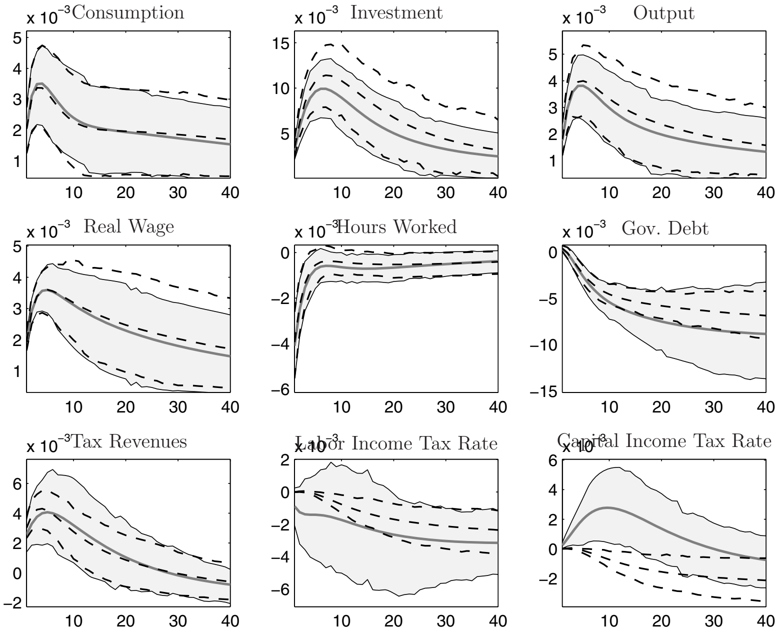


Figure 18: Bayesian impulse responses with new feedback rules (solid) and old feedback rules (dashed). Technology shock.

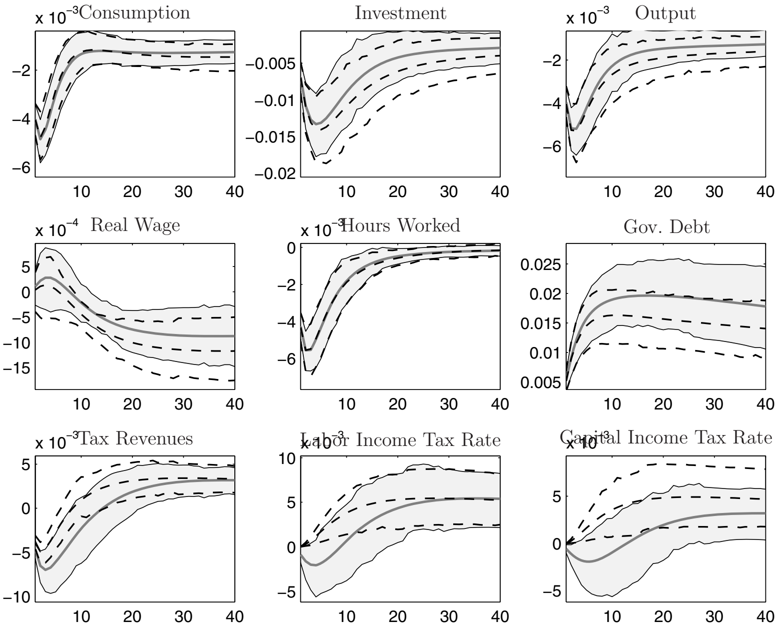


Figure 19: Bayesian impulse responses with new feedback rules (solid) and old feedback rules (dashed). Risk premium shock.

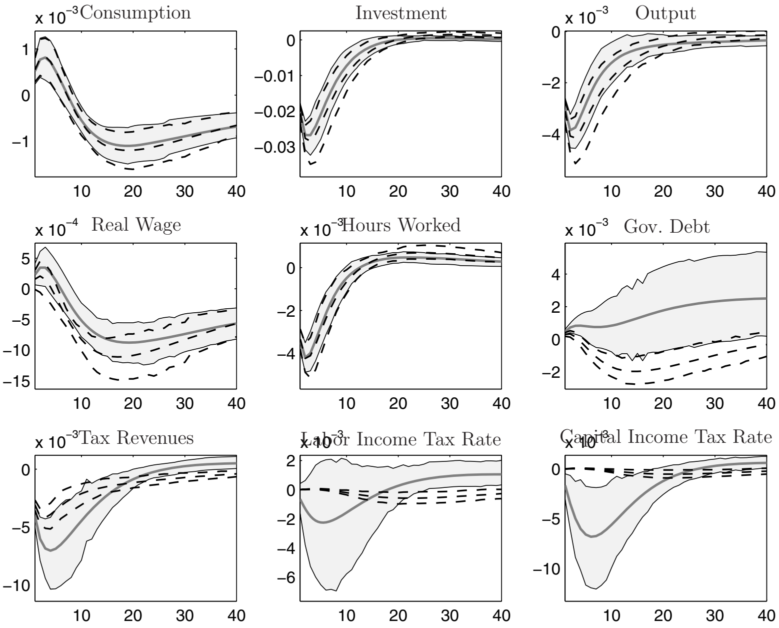


Figure 20: Bayesian impulse responses with new feedback rules (solid) and old feedback rules (dashed). Investment-specific shock.

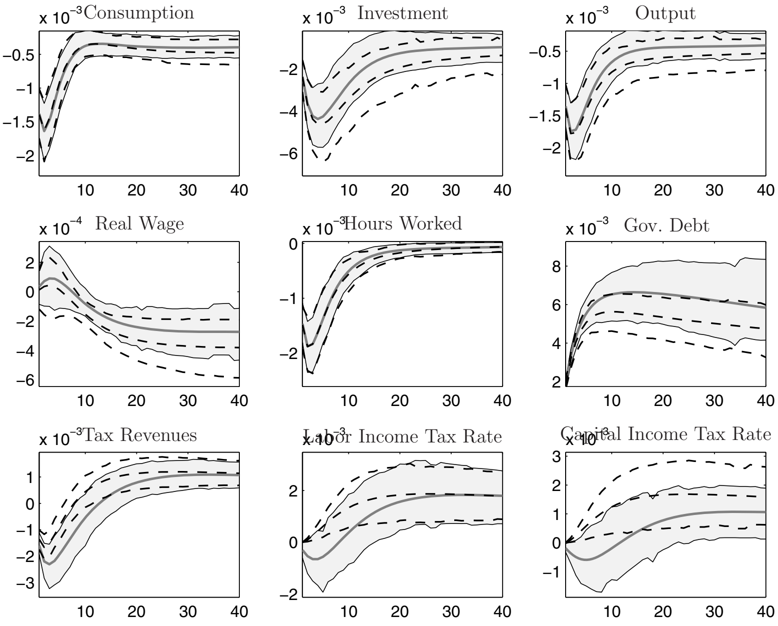


Figure 21: Bayesian impulse responses with new feedback rules (solid) and old feedback rules (dashed). Monetary policy shock.

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